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PACIFIC GAS AND ELECTRIC COMPANY

Digital Computer Simulation of a Hydroelectric Plant

Prepared in the Design Division, Department of Mechanical Engineering, Stanford University by Robert D. Regier under the direction of Professor Robert E. Keller. Valuable assistance from W. R. Johnson, J. E. Bussi, A. D. Gerhart, R. E. Morrison and J. E. Schumann is gratefully acknowledged as are the cooperation of the Pacific Gas and Electric Company and support of the National Science Foundation.

STANFORD UNIVERSITY

Design Division

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This case was written for a graduate system engineering course which emphasizes the mathematical representation of system components and the computer simulation of complex systems The case is used during the second and third quarters of the year long sequence. The students are introduced to component characterization and steady state analysis during the first quarter with an emphasis on electronic components and systems. In the second quarter techniques of digital computer system simulation are presented and the study of components is continued with a discussion of fluid power (mainly oil) systems. The case is introduced at this time, and the students are asked to prepare computer simulations of several components of the system with the turbine, penstock, and hydraulic control system being the items of major interest. In the last quarter the simulation of the complete plant, including attention to design objectives, is performed. The prerequisite for the course is a typical introduction to automatic feedback control and the usual preparation in mechanical or electrical engineering.

The case begins with a general discussion of the water power industry. Next, a typical hydroelectric plant, the Kings River Powerhouse, is described. Enough essential data on this plant is given to allow the student to use it as the basis for a computer simulation.

From an educational viewpoint the choice of a hydroelectric plant as a subject for study in depth has many valuable aspects. First, the system includes energy in fluid, mechanical, and electrical forms; the interesting similarities and interactions between these media are vividly exposed. Secondly, there are several academically interesting areas in the study, i.e., the penstock is one form of transmission line and exhibits the delay phenomena associated with such lines. Also, the turbine may be viewed as a three terminal device and characterized in the same form used for transistors, etc. The non-linearities, which are of both the smooth and discontinuous varieties, lead to other interesting problems. Lastly, the formulation of a useful set of design objectives by simulation is particularly challenging for the case of a hydro plant. The amounts of money involved are large, there are many external constraints on the design as well as a number of internal compatibility conditions, and the penalty for design misjudgments leading to failures, which are usually catastrophic, is severe.

The authors are indebted to Professor H. M. Paynter of the Massachusetts Institute of Technology whose interest in hydro stations and recognition of their educational usefulness provided the original concept for the case. Paynter's publications were also a great aid in

preparation of the case and will be found quite useful in preparation of the computer simulation.

The valuable assistance of the Pacific Gas and Electric Company is gratefully acknowledged. With a sense of due indebtedness to other P. G. and E. personnel special acknowledgement is given to the vital contributions of W. R. Johnson, J. E. Bussi, A. D. Gerhart, R. A. Morrison, and J. E. Schumann. While P. G. and E. has been very cooperative in supplying information and documentation to Stanford the company does not necessarily concur with any opinions expressed or authenticate the information supplied.

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GENERAL NOTES ON HYDROELECTRIC PLANTS

The Water Power Industry

During the past sixty years, many important changes have occurred in all branches of water power engineering. By 1900 the basic principles of hydroelectric power generation were firmly established along the same general lines now in use. Generation was usually accomplished by three phase generators wound for a voltage in the region of 3,000 to 10,000 volts. Direct distribution to a load was the most common system, but the interconnection of power stations was beginning on an experimental basis. Higher voltages, as high as 70,000 volts, were beginning to make their appearance. Now - sixty years later - operating voltages of 220,000 volts are common, several hydroelectric plants usually supply a load "network", and distribution of the electrical energy has increased in complexity. Many of the fundamental elements of hydro plants have, however, remained unchanged. The contemporary hydroelectric engineer is often confronted with design problems which are very similar to those of the earlier part of the century.

In the field of steam-turbine power generation, there is the possibility that some electro-chemical discovery (such as a fuel cell or a magneto-hydrodynamic device) might drastically alter the relative usefulness of steam turbine systems. However, the use of turbines and electromagnetic generators is the only method which has been suggested for commercially capturing the energy in falling water. Consequently, the hydroelectric plant is considered to remain an important area of engineering for at least several decades, and efforts to improve the design and operation of these plants should continue.

The use of electronics in controlling the frequency and output voltage of hydroelectric plants is increasing. With the steady expansion in size and range of interconnected power systems involving hydro, thermal, and nuclear plants and with the differing characteristics of these units, the question of system stability is likely to become increasingly important. During the next ten years computers may be used for the entire control of hydroelectric stations to yield greatly improved frequency and voltage

control. Changes of load distribution on a predetermined and automatically applied basis will be possible when system conditions make it desirable. The computer-controlled stations of the future are likely to use hydro power most economically by assessing total system demand at any instant in conjunction with data continuously fed into the computer memory. Such data will include incremental costs at adjacent fuel or nuclear-powered stations, cumulative rainfall data, available stream flow, transmission system loading, and forecasts of system demands over the next hourly and daily periods. From this data assessments may be made of the number of generator units to be activated and the duration of each unit's operation. Automatic starting, regulating, and stopping gear will then take control. Running units will be added as needed and every vital indication such as oil pressure, winding temperature, etc., will be monitored.

Before sophisticated automatic control can be applied to interacting power plants, it is necessary to have a complete understanding of the system performance under all possible operating circumstances. Therefore, an accurate understanding of the dynamic response of all plants in the system is necessary. The rapidity of response to changes in electrical load requirements and the quality of frequency and voltage regulation are a few of several important aspects of plant performance. The increased use of automatic control and the growing complexity of power systems will certainly increase the need for a thorough evaluation of plant operating characteristics.

These complex design and performance evaluation problems have indicated some shortcomings in current hydroelectric engineering analysis. During recent years many such problems have been tackled by means of calculations and assumptions which are based on past experience. This has served to reduce the analysis to a feasible degree of complexity. However, such methods are very often inadequate. Existing design situations and a clearly foreseeable increase in the need for a more extensive analysis of hydroelectric plants is stimulating a search for new approaches to these problems.

Computers in the Hydroelectric Industry

The advent of digital and analog computers and their application to hydroelectric design has produced results which can be made available more rapidly than is possible with manual computations. Accuracy has also improved. In some situations it has been possible to discard many of the simplifying assumptions and thus approach reality more closely. Although the idea of "mathematical models" is certainly not new, it was only when high-speed, large-capacity digital computers became available that these models could be developed for hydroelectric design work.

Computers are now finding valuable application in market projections, capacity analyses, engineering analyses of some plant components, and the solution of large computational problems. Computer simulations are being used increasingly in both process control and design in industries such as petroleum and aircraft. Much disagreement exists over the value of

simulating hydroelectric plant performance on analog and digital computers. Those who doubt the value of such simulation argue that complexity and uncertainty will prevent adequate simulation either for control or design purposes. They point out that design methods have been developed over several decades which are straightforward. Also, hydroelectric engineers are limited generally to the selection of "off the shelf hardware". They consequently feel that it is not worth the cost which might be required to develop truly representative computer simulations.

There are, however, arguments from authoritative engineers which allegedly justify the cost of computer simulations and strongly advocate an increase of their use in hydroelectric engineering. They assert that present design and performance evaluation could be improved substantially by employing simulation. Against the cost of useful simulation methods, they indicate the cost of the plants to be simulated, amounts in excess of $15 million not being uncommon. Although most hydroelectric plants designed without the aid of computer simulations have performed acceptably, some engineers believe that simulations would have allowed a more nearly optimal design.

Failures in Hydroelectric Plants

There are instances where present design procedures have clearly been inadequate, thus providing some evidence of the importance of doing the design job right. One example is the Kandergrund power station in Switzerland. The plant has a capacity of 20,000 hp and a head of 1,023 ft. A 13,800 ft. long tunnel was amply designed for this plant together with a surge tank which was over-designed for a system of this capacity. After a long period of operation, fissures had developed three times in the tunnel, each time at the same place; fissuration occurred again after repair of the tunnel lining. This was rather puzzling as it was thought that the exceptionally large surge tank should reject any large pressure waves. Subsequent fissures started a landslide which did severe damage to property and caused human lives to be lost. Much additional study showed that this failure was caused by an upper harmonic of resonance in the tunnel. Such behavior was completely unforeseen during the design of the plant.

Many other examples of resonance have occurred (which may be found in literature) and have amply demonstrated its nature and dangers. Resonance occurs suddenly and develops violently. Whatever the system of conduits considered - a single pipeline, pipelines with varying diameters, parallel pipelines, systems with surge tanks and a pressure tunnel - resonance at the fundametal frequency or higher harmonics may occur. Every detail of a hydro power station should be designed with the possibility of resonance being considered. The cost of failures in modern hydroelectric plants makes it imperative that this problem be investigated with the greatest care.

Computer simulations of such plants might be useful in discovering those conditions under which resonance could occur. Perhaps a simulation could be formulated which would allow one to predict the performance of a

plant more accurately than is possible using conventional design techniques. Also, it might then be possible to realize large savings by optimizing plant design. For most existing plants a one per cent decrease in design and construction costs would result in savings of over $100,000.

Standard Configuration of Hydroelectric Plants

The standard layout of a hydroelectric plant is illustrated in Figure 1. Water from the upper forebay enters the tunnel through an intake structure. Most of the horizontal distance between the upper reservoir and the power plant is traversed by the tunnel while the change in elevation is accomplished by the penstock. A surge tank at the junction of the penstock and tunnel attenuates transient pressure changes due to variations in turbine water requirements. The water transfers most of its energy to the turbine runner and subsequently enters the tailwater channel. The turbine drives a generator which delivers power to a voltage step-down transformer. The transformer terminates in a transmission line which appropriately distributes the electric power to the system load.

Most hydroelectric plants are of the general form just described, although individual plant arrangement does vary. For example, some plants have two surge tanks and multiple penstocks operating in conjunction with one or more turbines. The Kaplan, Francis, and Pelton are the most frequently used types of turbines. The available head, flow rate, and desired characteristics of the output specify the turbine to be used in a particular installation.

A hydroelectric plant will now be described which is typical insofar as it has the general arrangement discussed above. Attention will be focused on the Kings River Powerhouse, which is located 40 miles southeast of Fresno, California, adjacent to the North Fork of the Kings River. The succeeding sections of the case will describe the basic physical dimensions and layout of this plant.

DESCRIPTION OF THE KINGS RIVER POWERHOUSE

The Kings River Project

This hydroelectric development is located on the North Fork of the Kings River. It utilizes a 5600 foot drop in the river for the generation of 296,000 kilowatts of power which is carried through a distribution network for use in northern and central California. The Wishon reservoir on Helms Creek forms the headwater for this development. During its descent the water travels approximately 40 miles through the Sierra and Sequoia National Forests. A map and profile of the project is shown in Figure 2.

The Kings River Powerhouse - General Description

The Kings River Powerhouse operates under a static head of 793 feet and has a peak output capability of 42,000 kilowatts. During maximum output the water flow is 760 cubic feet per second.

Water is carried from the Balch Powerhouse afterbay through a tunnel system to a point above the powerhouse where connection is made with the penstock. The tunnel system is composed of two tunnels and an inverted siphon. The two tunnel sections are separated by a ravine which contains the Dinkey Creek. From the upstream half of the tunnel the siphon transports the water down one side of the ravine and up the other. Flow then continues through the second section of the tunnel to the penstock. At the junction of the tunnel and penstock is a surge tank which prevents large water pressure surges in the tunnel and penstock during changes in electrical load.

The penstock carries water to the turbine and accounts for most of its change in vertical elevation. The turbine is a vertical reaction type (also called a Francis turbine) and is solidly connected to a generator through a large shaft. Water enters the turbine through a spiral-shaped case where its flow is controlled by 24 wicket gates. The water then transfers most of its energy to the rotating turbine runner, enters a draft tube, passes on to the tailrace, and flows to the Pine Flat Reservoir. An external view of the plant with an abnormally and almost intolerably high level of tailwater is shown in Figure 3. Such high tailwater is very uncommon but will occur when Pine Flat Lake is at maximum capacity. The tailwater level seen in Figure 4 is normal. The elevation of tailwater never varies more than two feet as a result of changes in wicket gate setting. A 250 ton gantry crane used during construction is also shown in Figure 4.

A governor and hydraulic servomechanism controls the turbine speed by adjusting the wicket gate position. A speed-sensing device detects any error in generator speed and initiates corrective governor action

which results in an appropriate change of wicket gate setting. When the wicket gates close (corresponding to a decrease in electrical load) the inertia of the water tends to cause a pressure rise in the penstock. If the wicket gates close rapidly enough, a pressure regulator opens in synchronism with wicket gate closure to bypass some water around the turbine and, thus, limit the penstock pressure. The pressure regulator then gradually closes as the flow rate in the penstock decreases. This is the most common function of the pressure regulator, although other modes of operation are possible and will be discussed later.

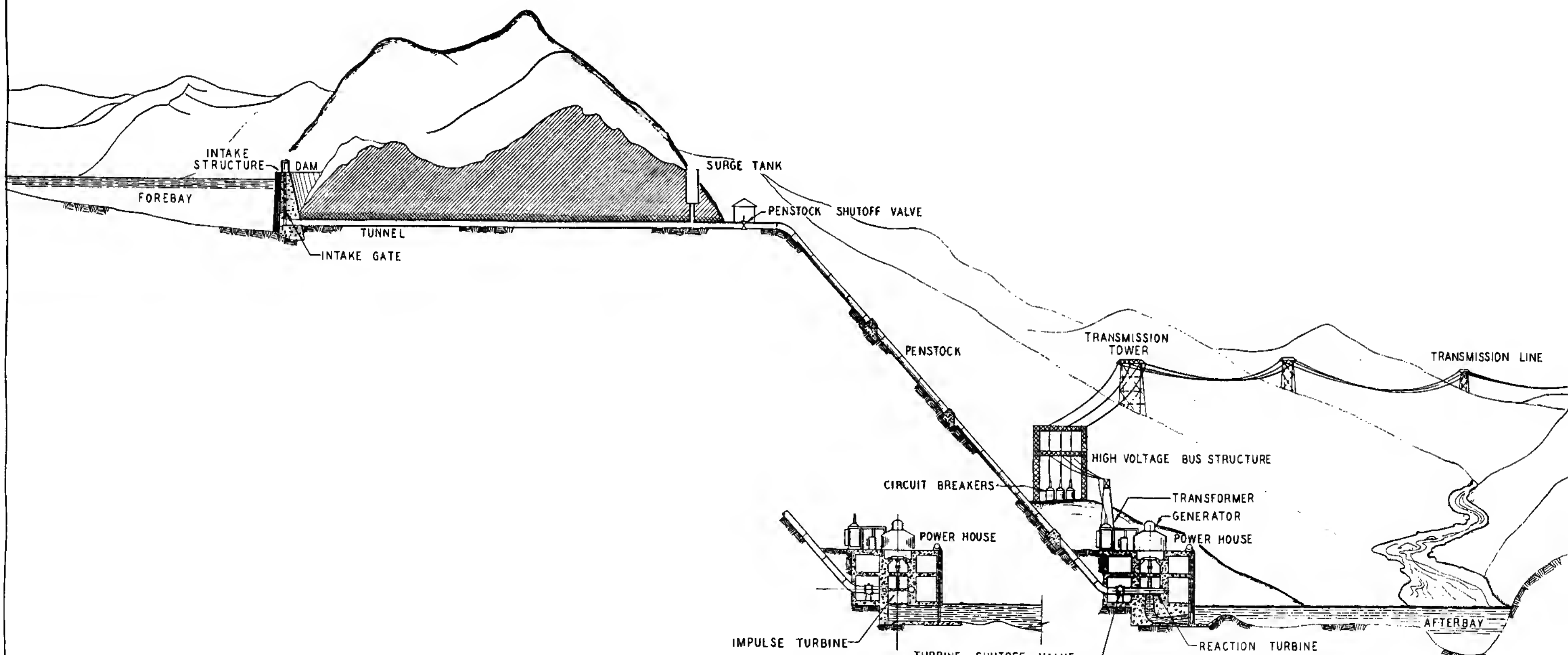
The AC generator is rated at 49,000 kva at 13,000 volts, 60 cycles, when operating at 360 revolutions per minute. The generator is a vertical shaft type and is mounted directly above the Francis turbine. Field excitation is provided by a DC generator directly connected to the top of the AC unit. A voltage regulator maintains a nearly constant load voltage by appropriately adjusting the output voltage of the DC generator. A three-phase transformer is used to transform the 13,000 volt power produced by the generator to 110,000 volts for transmission. Such a turbine generator unit is illustrated by Figure 5.

The Tunnel and Siphon

A photograph of the Balch Powerhouse afterbay, dam, and tunnel intake structure is shown in Figure 6. The screens on the exposed face of the structure prevent the passage of dangerously large pieces of debris. A float, which is protruding above the lake surface in the photograph, normally floats on the lake and keeps the inlet free of large obstacles such as logs. The intake assembly also contains vertical tubes or float-wells which house floats that measure the afterbay and tunnel water levels. A large differential in these measurements would indicate a ruptured penstock or siphon and supervisory controls would immediately close the tunnel intake gate.

A 9045 foot tunnel section extends from the Balch Powerhouse afterbay to the Dinkey Creek siphon. Another section, 9501 feet in length, extends from the siphon to the surge tank and outlet portal where the penstock is connected. Excepting the portals (points where the tunnel joins the siphon or penstock), the tunnel is unlined and has a horseshoe-shaped cross-section as illustrated in Figure 7. The base of the tunnel is 14 feet wide; the parallel vertical sides are 7 feet high; and the radius of the top is 7 feet. Factors such as tunnel construction costs, friction loss, flow rate, and erosion of tunnel surface determine the tunnel dimensions. Figure 8 shows a construction phase of the portal in the upstream tunnel section looking across Dinkey Creek Canyon towards the inlet portal of the downstream tunnel. Except for the portals only a minor amount of concrete was necessary, this being in several short sections of the tunnel where the rock was badly fractured. The rails and large pipe that appear in Figures 7 and 8 are removed after construction is completed. The pipe brings in fresh air during drilling and pumps out products of combustion after blasting. A profile of the tunnel appears in Figure 9.

The siphon is of steel construction and is solidly embedded at each end where it joins the tunnel. At several points steel straps securely



TYPICAL HIGH HEAD
MULTI-JET
IMPULSE TURBINE
INSTALLATION

TYPICAL MEDIUM HEAD
REACTION TURBINE
INSTALLATION

Figure 1 - Standard Plant Configuration

TYPICAL HYDRO-ELECTRIC DEVELOPMENT

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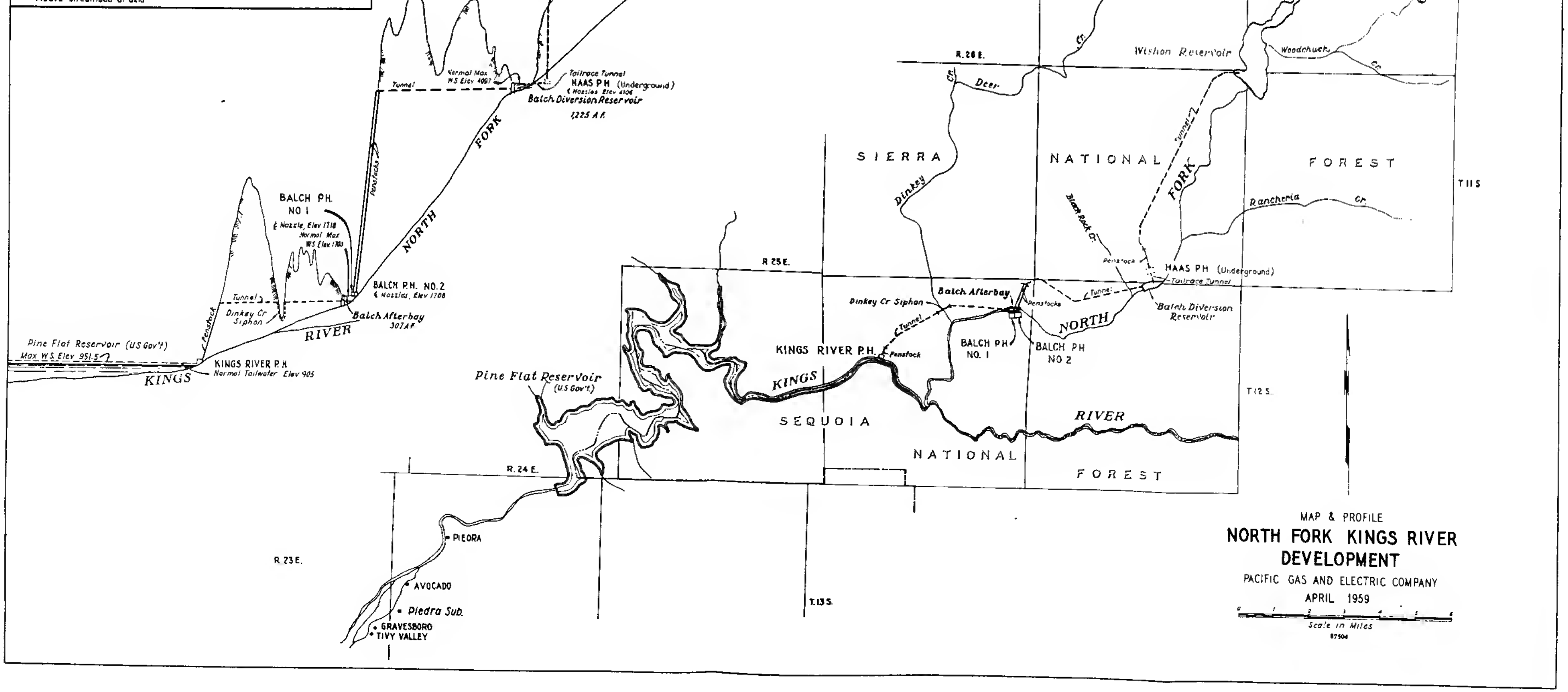
Figure 2 - Kings River Project

PHYSICAL DATA

	COURTRIGHT	WISHON	HAAS	BALCH NO 1	BALCH NO 2	KINGS RIVER
HEAD						
Static - ft.			2,444	2,379	2,369	793
FLOW (design)						
Peak - c.f.s			760	200	560	760
OUTPUT (design)						
Peak kw			128,000	32,000	94,000	42,000
Energy - mil. kwh			398	477		153
DIVERSION AND/OR STORAGE DAM						
Type	Rock Fill	Rock Fill		Arch		Arch
* Height - ft	295	256		118		118
Effective Capacity - A.F.	123,300	128,400		970		135
CONDUIT						
Tunnel - size - ft			13' Ω	12 x 12		13' Ω
length - ft			32,691	19,336		18,570
Siphon dia - in						108 to 98
length - ft.						2000
Tailrace Tunnel - size - ft			15' x 17'-6" Ω			
length - ft.			1963			
PENSTOCK						
Pipe - No. & Dia - in			1 @ 96 to 78	1 @ 60 to 48	1 @ 96 to 68	1 @ 96 to 88
length - ft			4363	4980	4952	1860
INSTALLATION						
Number of Units			2	1	2	1
Total Prime Mover - H.P.			184,000	40,000	184,000	60,000
Total Generator - Kva			150,000	33,000	106,000	48,000

* Above streambed at axis



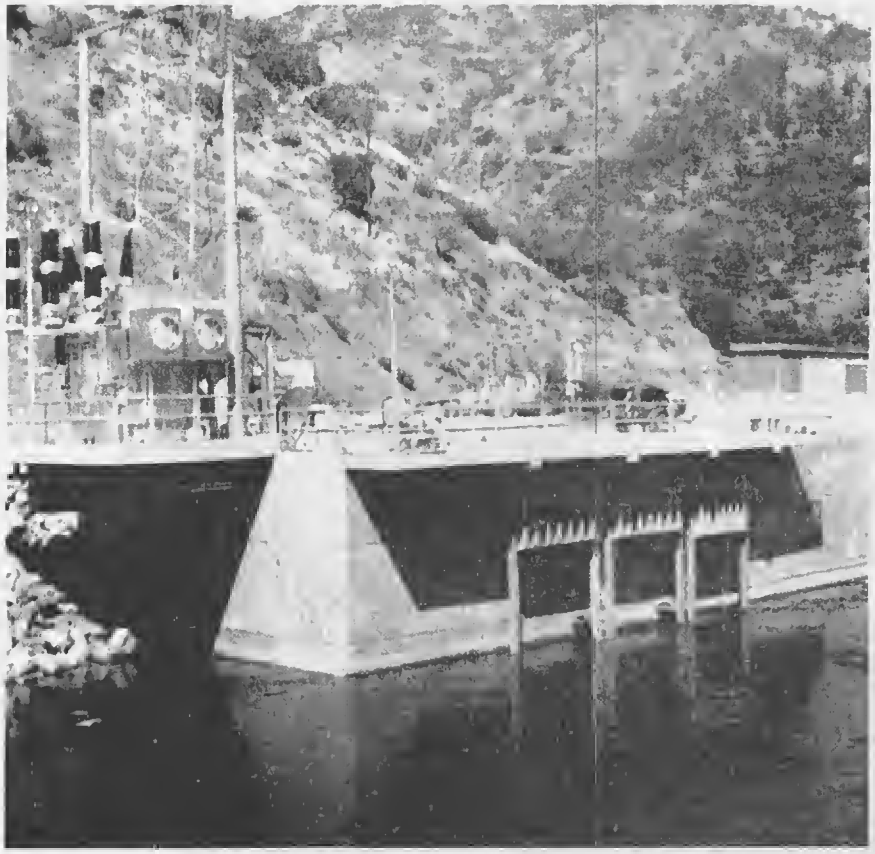


Figure 3 - Plant During High Tailwater

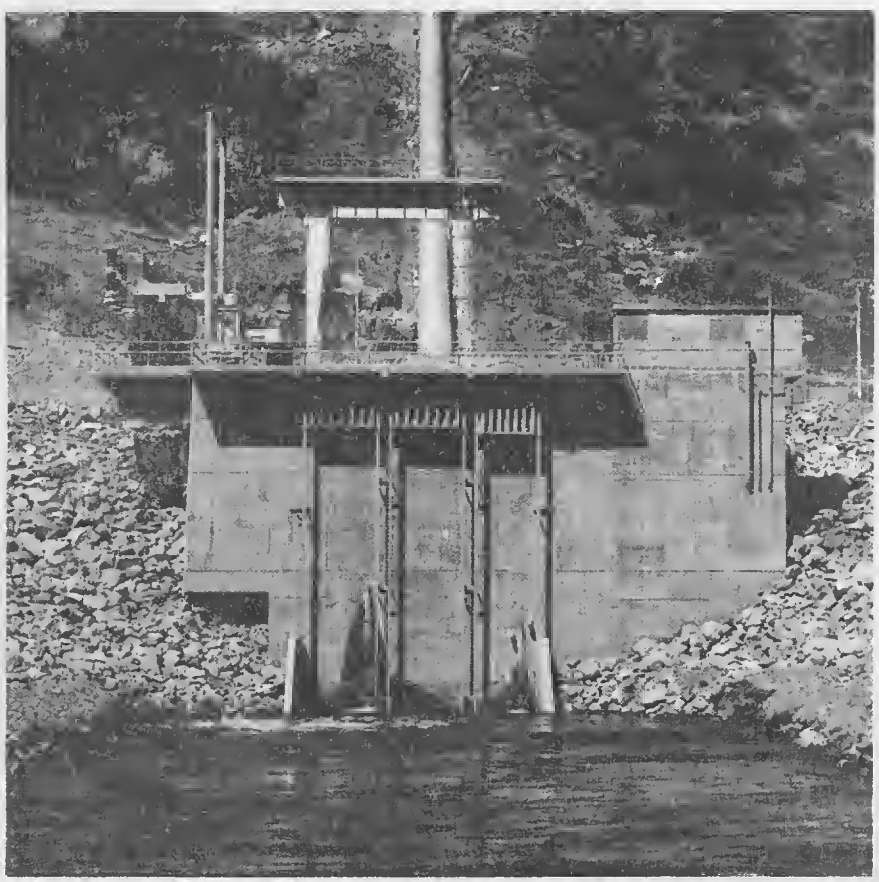


Figure 4 - Plant During Normal Tailwater

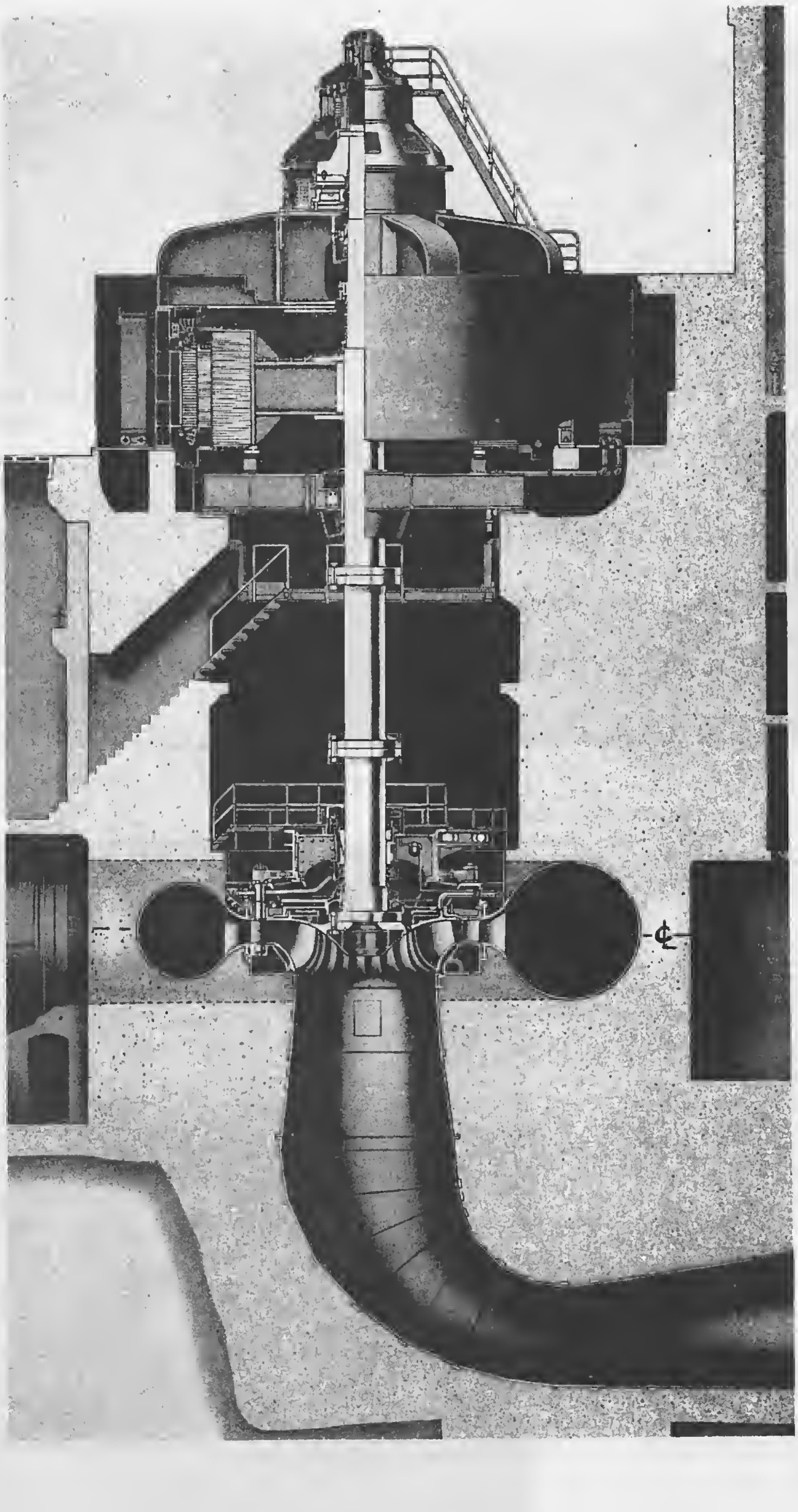


Figure 5 - Turbine Generator System

Figure 6 - Tunnel Intake Structure

Figure 7 - Regular Tunnel Cross-Section

Figure 8 - Tunnel Cross-Section at Portals

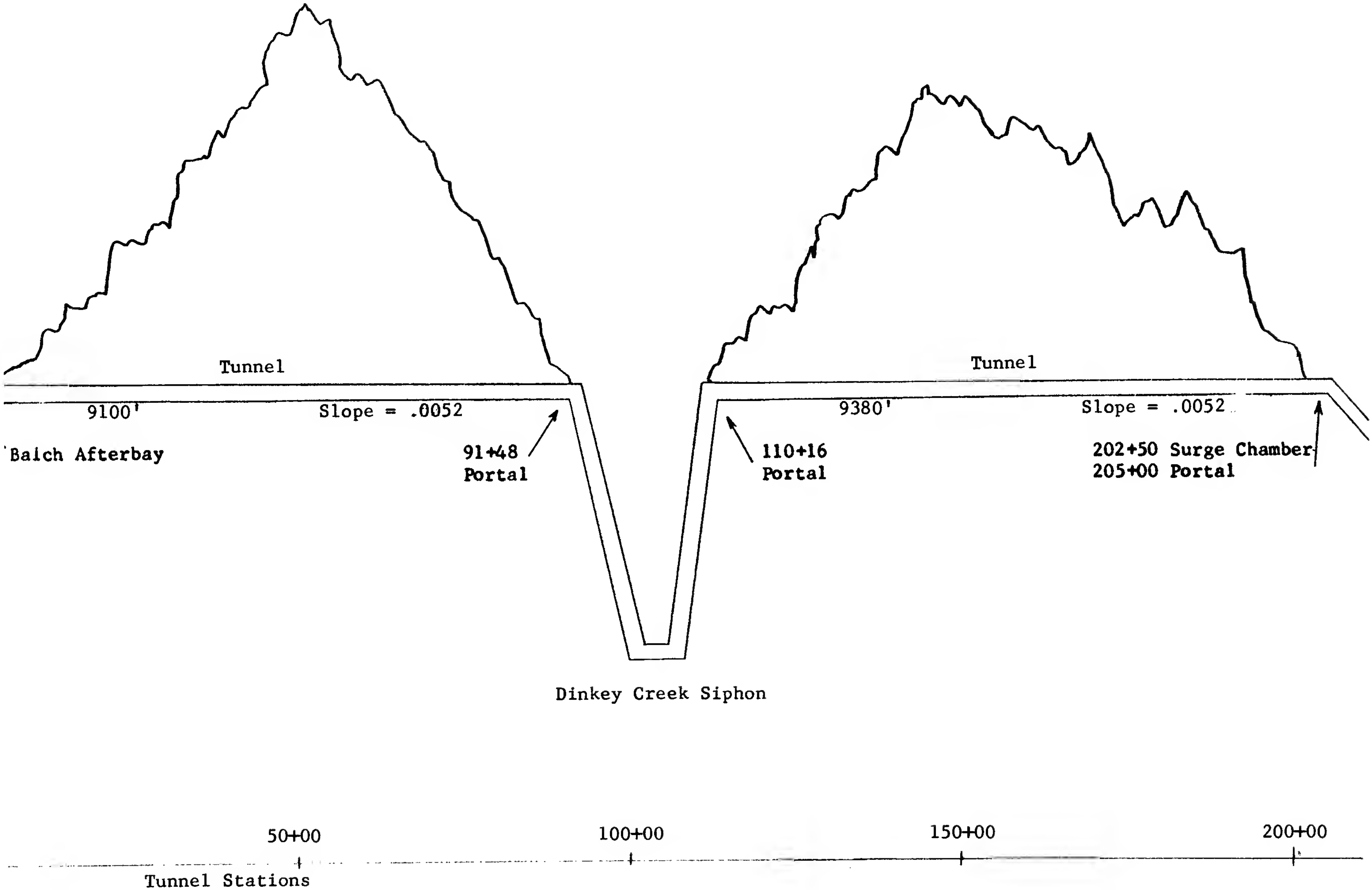


Figure 9 - Tunnel Profile

fasten the siphon to concrete abutments in the ground, and a gradual taper exists at all transitions of pipe diameter. A photograph and profile of the siphon are contained in Figures 10 and 11

The Penstock

The steel penstock is circular in cross-section with dimensions as indicated by Figure 12. The penstock is solidly attached to large concrete structures at points where its slope or alignment changes and at several other points along its length. A portion of the penstock located just below the surge tank appears in Figure 13.

An important consideration in penstock design and performance is waterhammer. Waterhammer is a transient change in pressure which will occur when the gate used to control water flow through the turbine is either opened or closed

Surge Tanks

The surge tank is a large water storage chamber at the top of the penstock which prevents dangerous pressure rises in the tunnel and penstock when the flow rate through the turbine is suddenly decreased. The tank also acts as a quick supply of water when the wicket gates open and the water velocity in the tunnel does not increase at a sufficient rate. Similarly, a decrease in wicket gate opening will cause additional water to be stored. Changes of electrical load and consequent changes in wicket gate position cause the level of water stored in the surge tank to rise or fall, thus decreasing the magnitude of pressure changes in the tunnel and penstock. The necessary storage capacity of a surge tank decreases as the tunnel length or rate of load change decreases.

Surge tanks may roughly be divided into three classes: simple, restricted, and differential. These are shown in Figure 14. The simple tank is suitable from the governing point of view, since it produces very gradual changes in head and allows the governor to follow pressure changes with little difficulty. However, since damping is relatively low, variations of surge tank level may not be adequately attenuated. The restricted tank is very effective in attenuating such variation, but, due to its high damping, may not provide adequate pressure regulation. The orifice area in a restricted tank is typically 15 to 30% of the tunnel area. Differential tank performance is a compromise between that of the other types since its riser acts as a source of readily available water and its orifices provide the necessary damping. The operating characteristics of this type of tank are controlled by the size of orifices and the storage capacity of the riser column. When designing a surge tank, penstock construction costs and the advantage of rapid load change must be weighed against surge tank costs

The Kings River Powerhouse surge tank is a differential type. The unit consists of a twenty-foot diameter pipe extending vertically above the tunnel and terminating in a chamber which is 60 feet in diameter and 20 feet high. In the center of the chamber is a ten-foot diameter riser

Section	Length(ft.)	OD(in.)	Thickness(in.)
1	75	108	.275
2	464	108	.375
3	185	102	.438
4	401	98	.500
5	296	102	.438
6	468	108	.375
7	125	108	.375

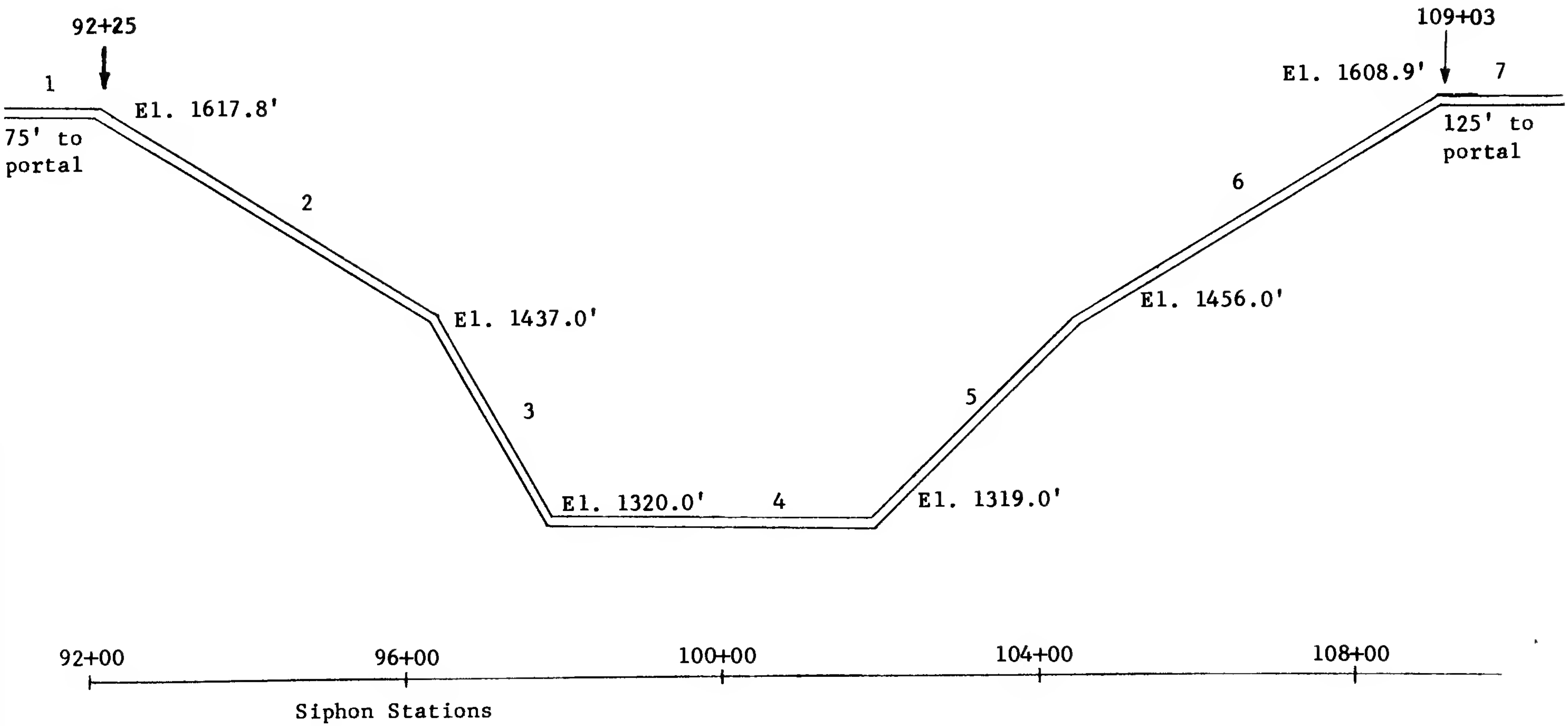
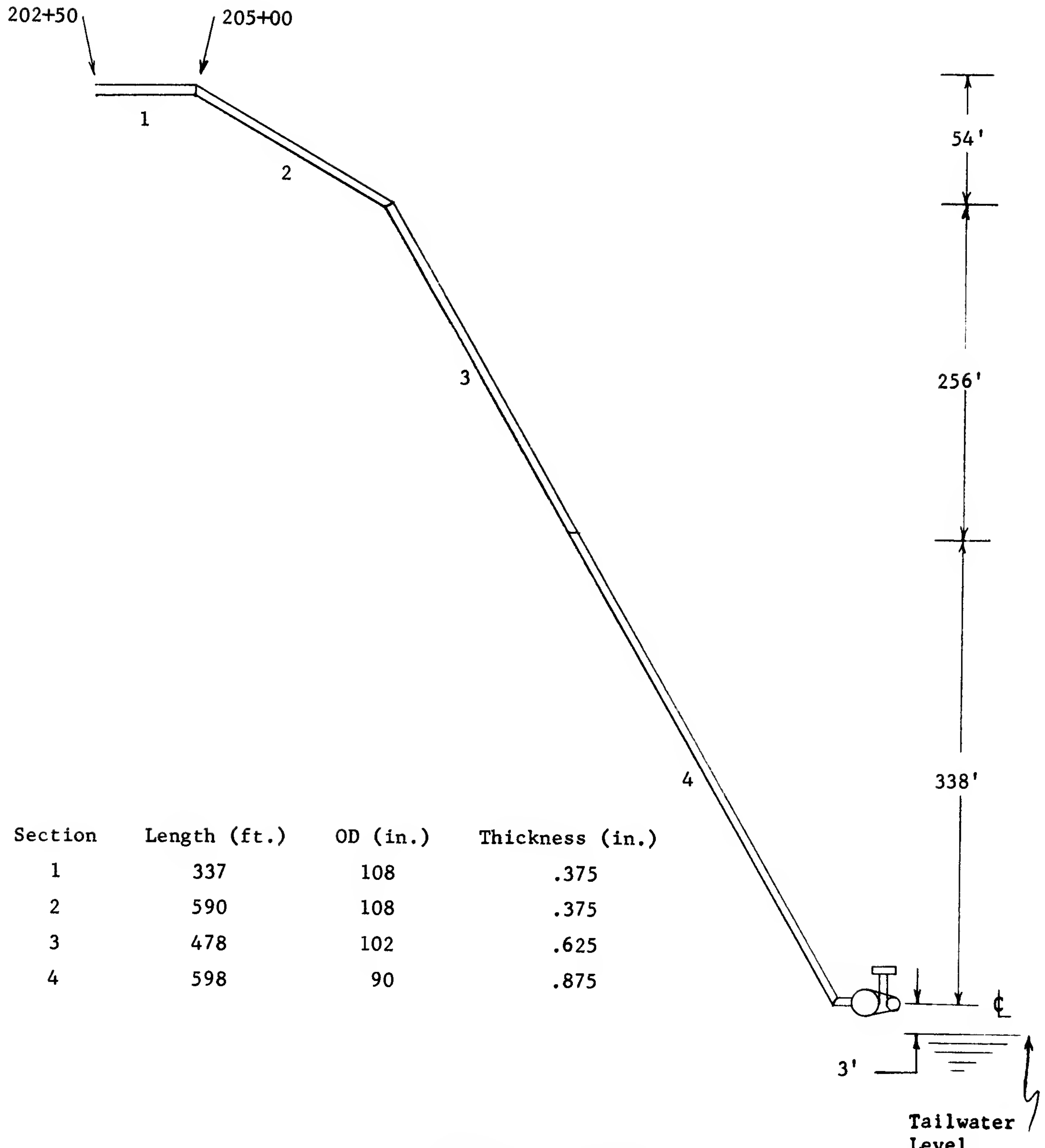


Figure 10 - Profile of Dinkey Creek Siphon

Figure 11 - Dinkey Creek Siphon



Section	Length (ft.)	OD (in.)	Thickness (in.)
1	337	108	.375
2	590	108	.375
3	478	102	.625
4	598	90	.875

Figure 12 - Penstock

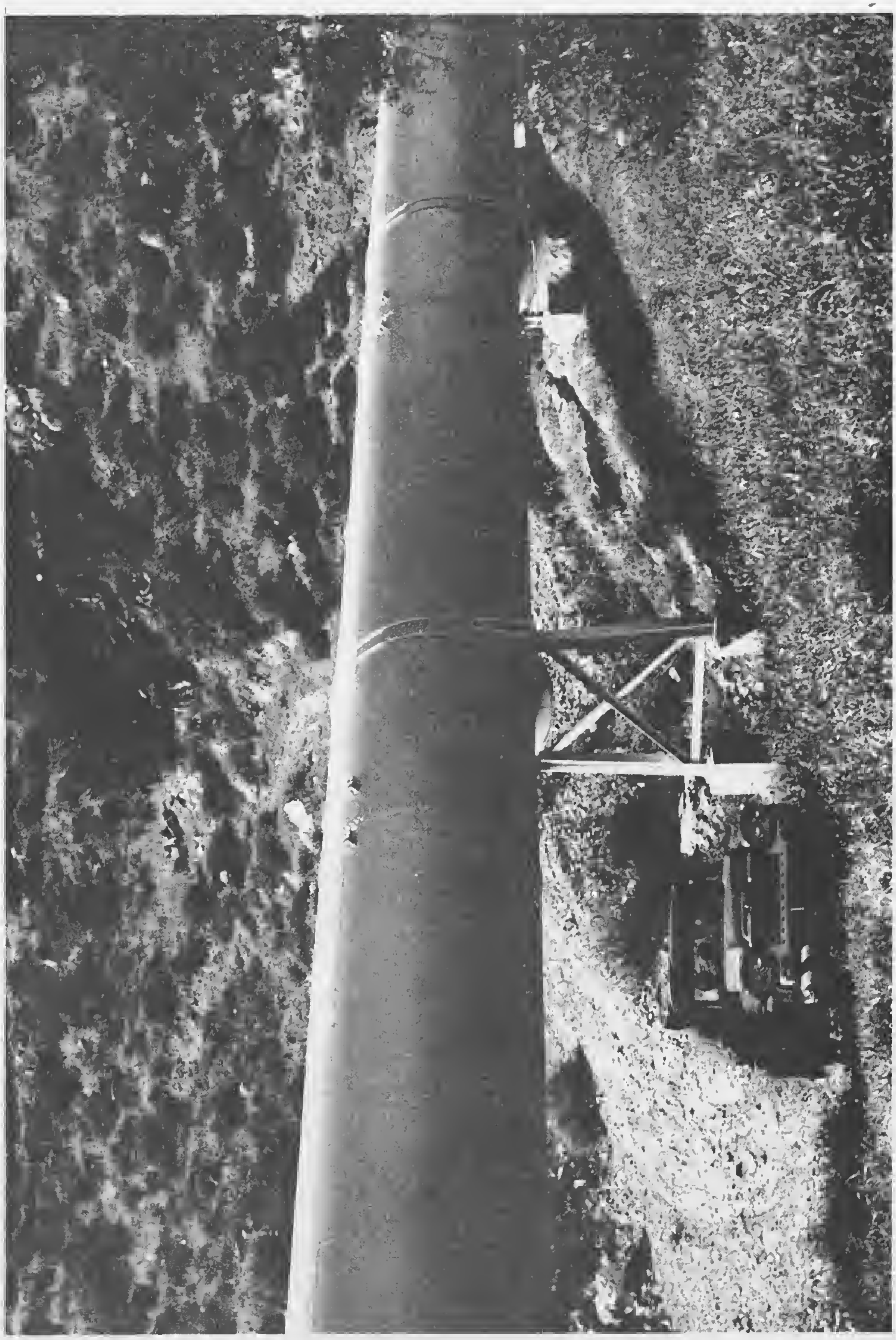


Figure 13 - Penstock Section

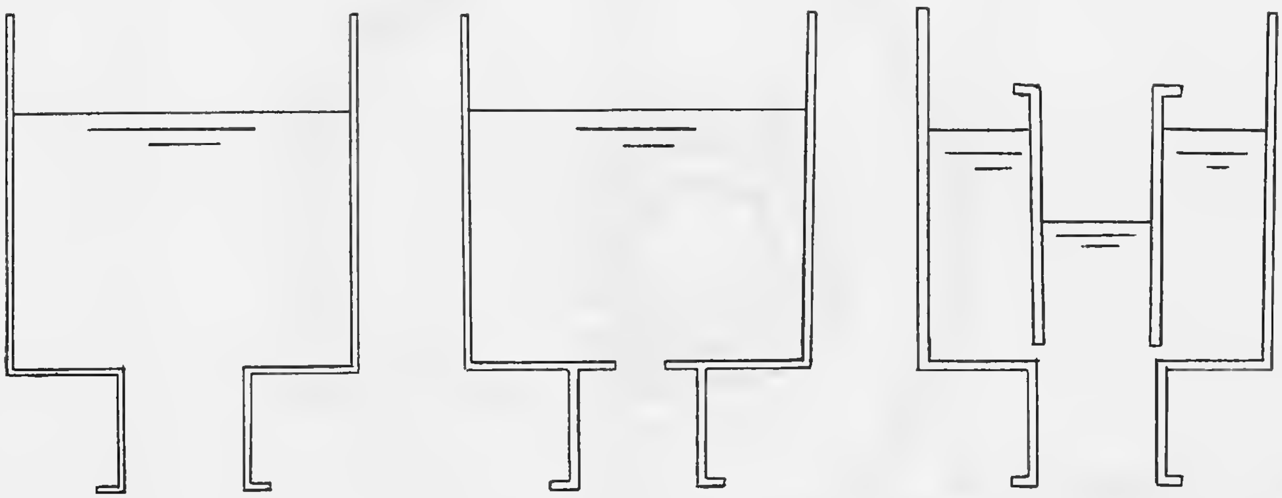


Figure 14 - Types of Surge Tanks

Figure 15 - Surge Tank Riser and Portals

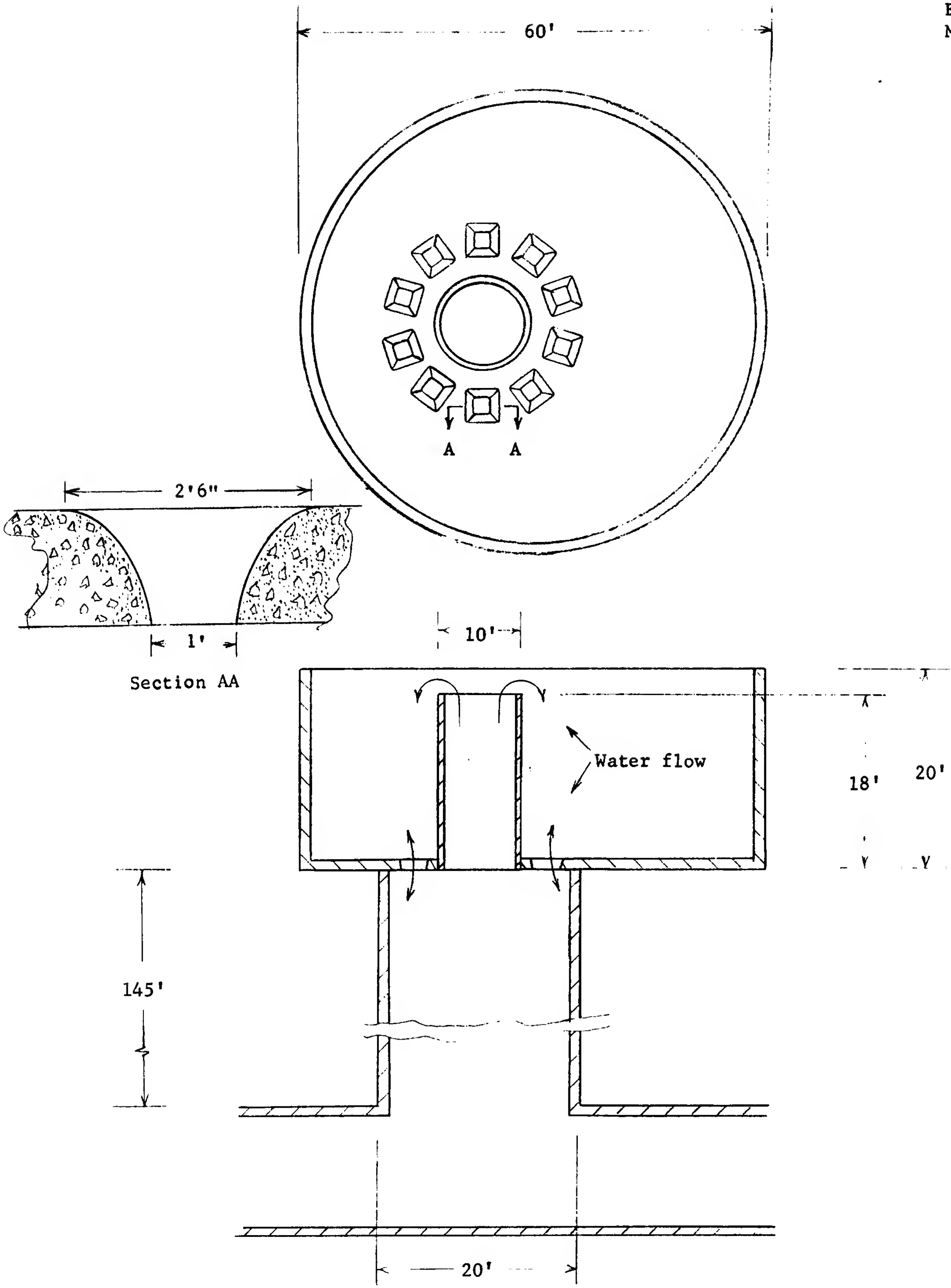


Figure 16 - Surge Tank

as indicated by Figures 15 and 16. This surge tank will often act as a simple tank since the water frequently remains below the orifices during a change in flow rate. When electrical output power is decreased fast enough, however, water will pass through the orifices. Initially, the tank designed for the Kings River Powerhouse was a simple tank (20' diameter) inside an overflow tank (60' diameter). The overflow pipe was subsequently made smaller to take advantage of differential action during high forebay water levels.

Pressure Regulator

The pressure regulator prevents dangerous variations of penstock pressure as the position of the wicket gates is rapidly changed. As the wicket gates close, water inertia in the penstock tends to create a rise in pressure. To diminish this transient pressure change, the regulator temporarily by-passes some water around the turbine. After the system is restored to steady state operation, the flow rate through the penstock may be less than or equal to that which existed before wicket gate movement. The particular steady state flow will depend on the mode of pressure regulator operation. A schematic of the regulator is given in Figure 17, and a photograph of the exterior appears in Figure 18.

The two extremes of all possible modes of operation correspond to the full by-pass and full water-saving settings of the regulator. During 100% by-pass operation the pressure regulator acts to maintain a constant penstock flow rate over the full range of wicket gate settings. To achieve this performance the adjusting screw is raised via the motor or handwheel until the adjusting screw is bearing on the bottom of the eyebolt. The dashpot will then be inoperative and the pilot valve will operate directly with the servomotor stroke. Thus, when the wicket gates move towards the closed position, the dashpot cylinder will move up causing the pilot valve in the balance cylinder to open. This allows water in the balance cylinder to flow through the main plunger and out to the tailrace. The pressure on top of the balance cylinder is now less than on the bottom because water cannot pass through the balance piston-cylinder clearance as fast as it escapes through the open pilot valve. Consequently, the main plunger raises a corresponding amount and remains open because the adjusting screw prevents the pilot valve from lowering.

Full water saving operation is obtained by lowering the adjusting screw enough to prevent it from ever bearing against the eyebolt. With such an adjustment, the dashpot piston and pilot valve move at a rate controlled by the dashpot valve openings. In a steady state the main plunger and pilot valve will be closed regardless of the wicket gate position. Thus, in the water saving mode the pressure regulator merely promotes a gradual change in penstock flow rate as the wicket gates move. During steady state operation and slow wicket gate motion no water is by-passed around the turbine.

Between these two extremes the pressure regulator may be adjusted to by-pass any desired amount of water in a steady state. This is accomplished by setting the adjusting screw to an intermediate position.

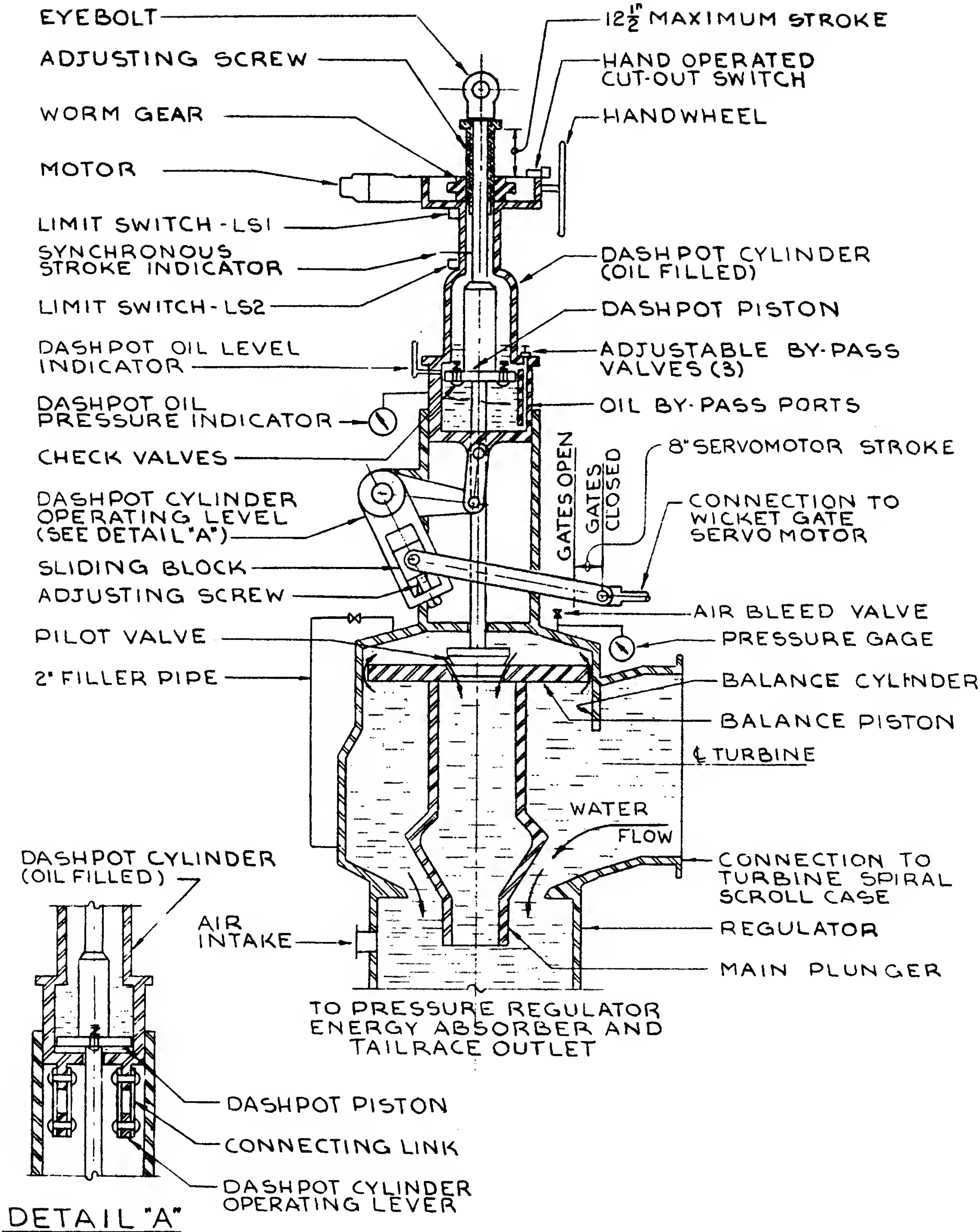


Figure 17 - Pressure Regulator Schematic

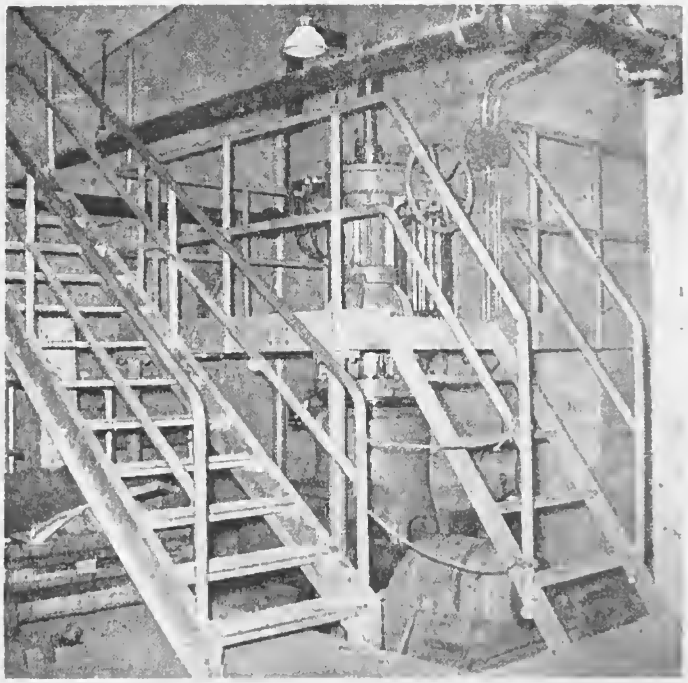


Figure 18 - Pressure Regulator

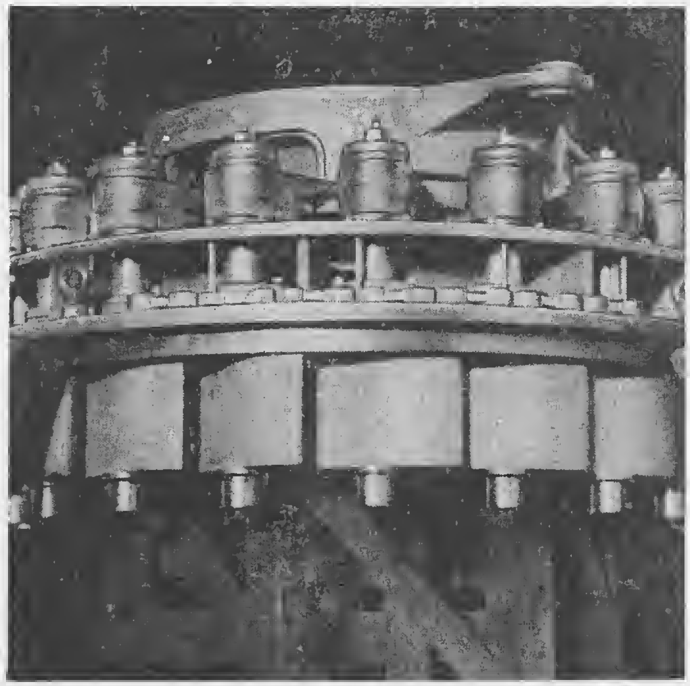


Figure 20 - Wicket Gates

Figure 19 - Scroll Case

Other pressure regulator data is the following:

Mass of main plunger	16.1 lb. sec^2/in.
Balance piston diameter	4.7 in.
Balance piston-cylinder gap	.01 in.
Max. travel of dashpot cylinder	11.0 in.
Main pilot valve diameter	10.0 in.

The Wicket Gates

As water flows from scroll case to turbine runner its direction and area of flow is controlled by the wicket gates. A photograph of the scroll case and its stationary stay vanes during construction appears in Figure 19. The wicket gates are subsequently installed between the stay vanes and turbine runner. Figures 20 through 22 illustrate the visual placement and operation of wicket gates; the basic operation of the units shown is the same as that of the Kings River Powerhouse gates. The shafts which turn the gates extend upward through a stationary ring as shown in Figures 20 and 21. The gate rotation occurs when the inner gate ring is moved by the governor servomechanism. Gate ring motion is transmitted to the individual gate shafts by linkages on top of the gate assembly. Figure 22 is a photograph of some wicket gates installed in a scroll case. These gates are shown in the closed position just behind the stay vanes as viewed from inside the scroll case. The sketches and photographs of Figures 23 through 25 illustrate the layout of the wicket gates in the Kings River Powerhouse. A large pipe from the pressure regulator attaches to the scroll case at the joint which is partially visible in the upper left corner of Figure 19.

When the wicket gates are open, water leaves the scroll case in a radially inward direction, and, after passing through the turbine runner, is discharged in an axial (vertical) direction. The action of the wicket gates is more than a simple throttling action; by their rotation the angle at which the water strikes the turbine blades is varied.

The gate ring is moved by a servomechanism which in turn is activated by the governor. The relationship between wicket gate position and servomotor displacement is given in Figure 26. The forces which must be overcome by the servomotor vary with gate position. Most wicket gate systems are designed so that during the opening portion of the gate stroke water tends to force the gate open and for the remainder of the stroke tends to close it. This force distribution promotes fast governor action and good regulation. As a closed position is approached, resistance to closure increases, reaching its maximum at the fully closed position. This makes best use of governing gear inertia and at the same time prevents slamming of the gates. The wicket gates are designed to give the best balance of hydraulic forces over the useful range of openings. Nevertheless, the forces which must be overcome by the servomotor are considerable. Experimental data by Vaughan (Reference 11) should be helpful in describing the nature of the forces usually encountered

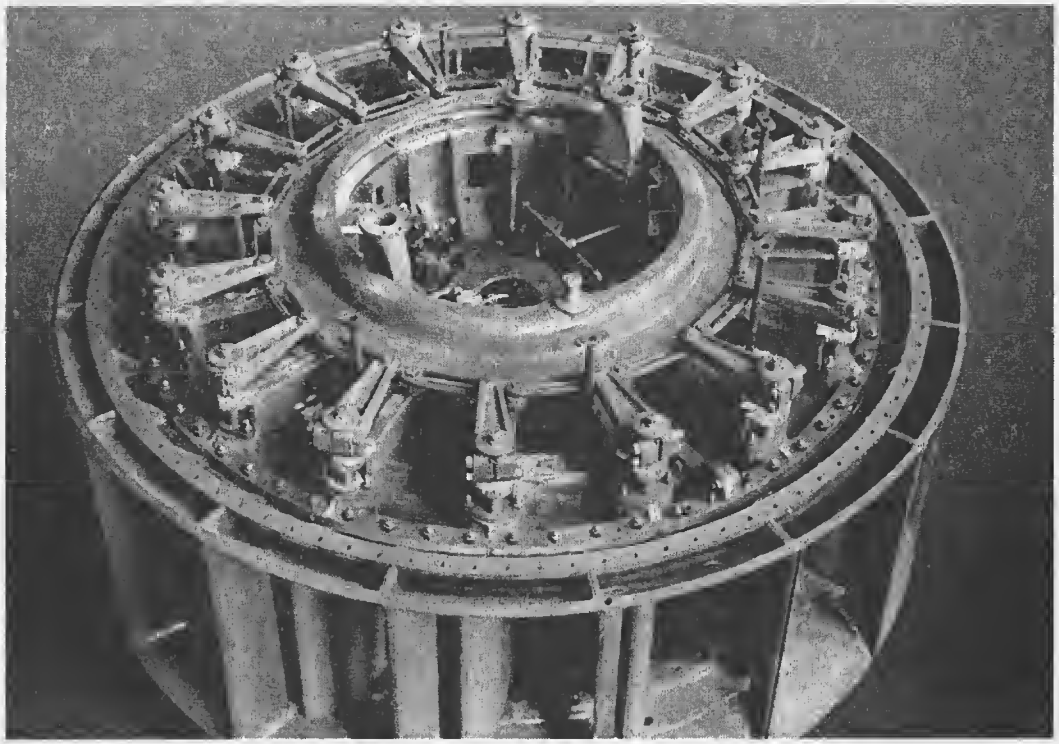


Figure 21 - Wicket Gates and Stay Vanes

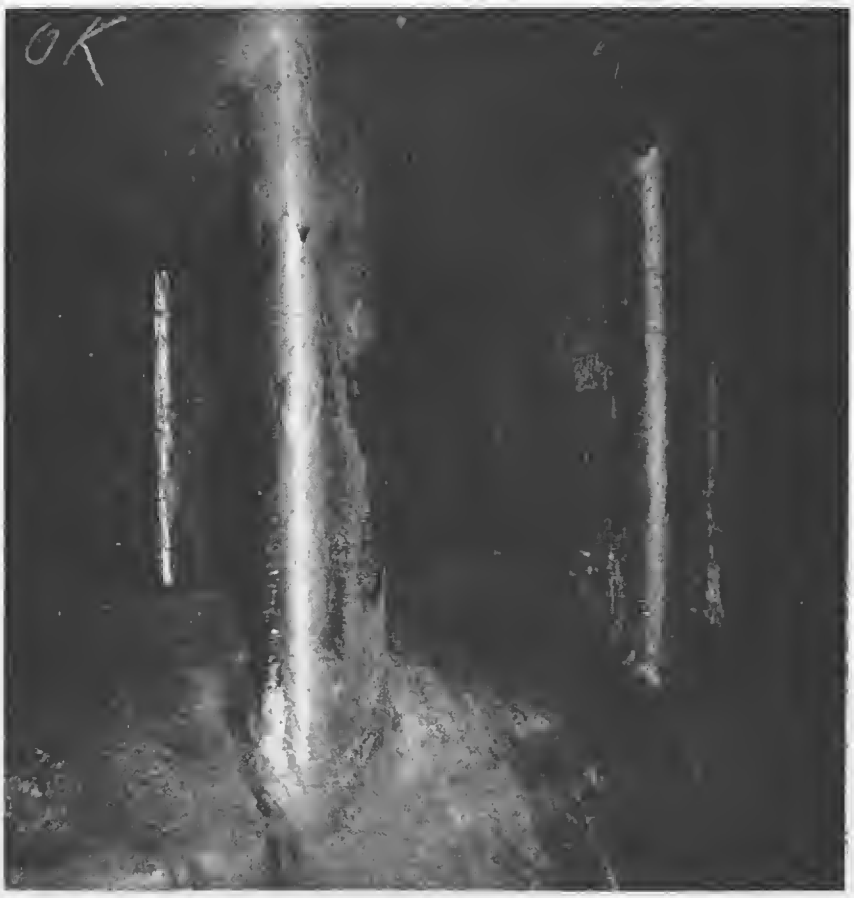


Figure 22 - Wicket Gates Installed in Scroll Case Behind Guide Vanes

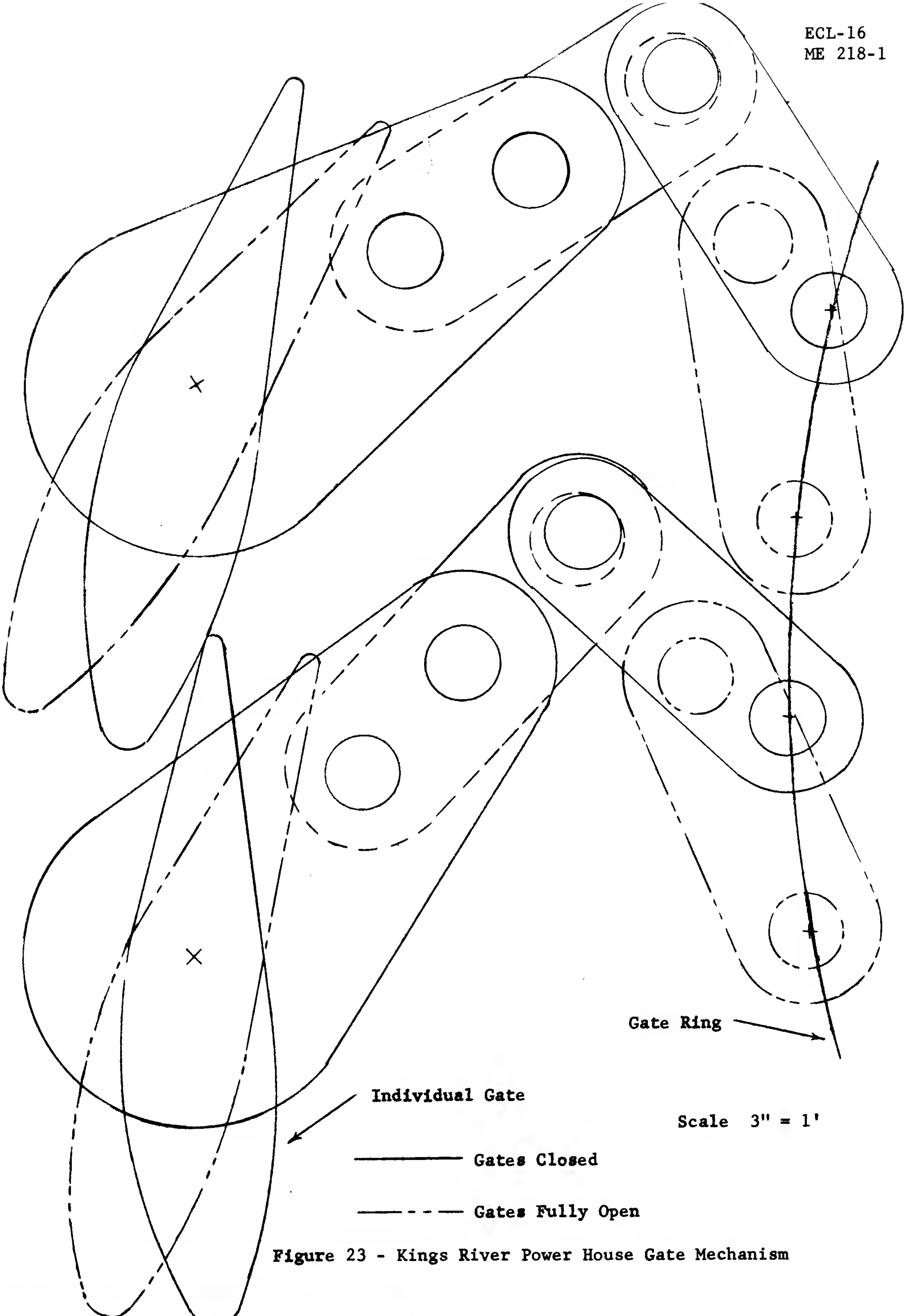


Figure 23 - Kings River Power House Gate Mechanism

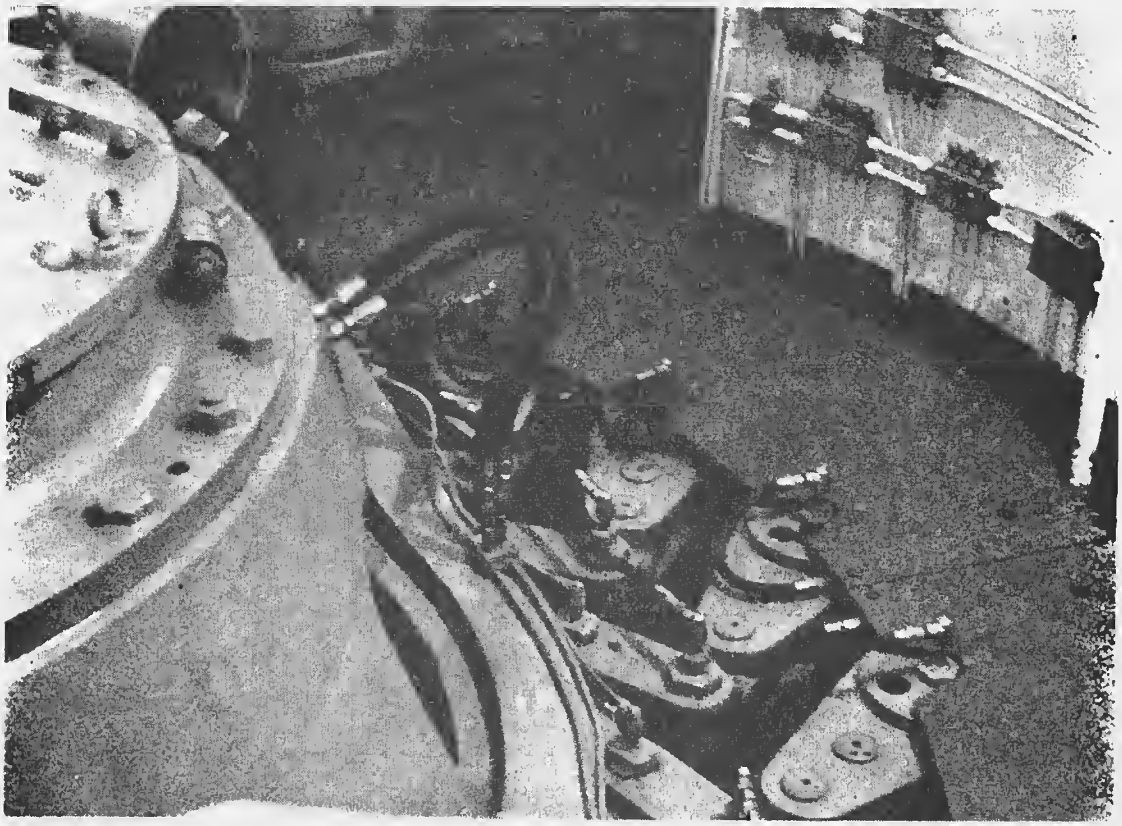
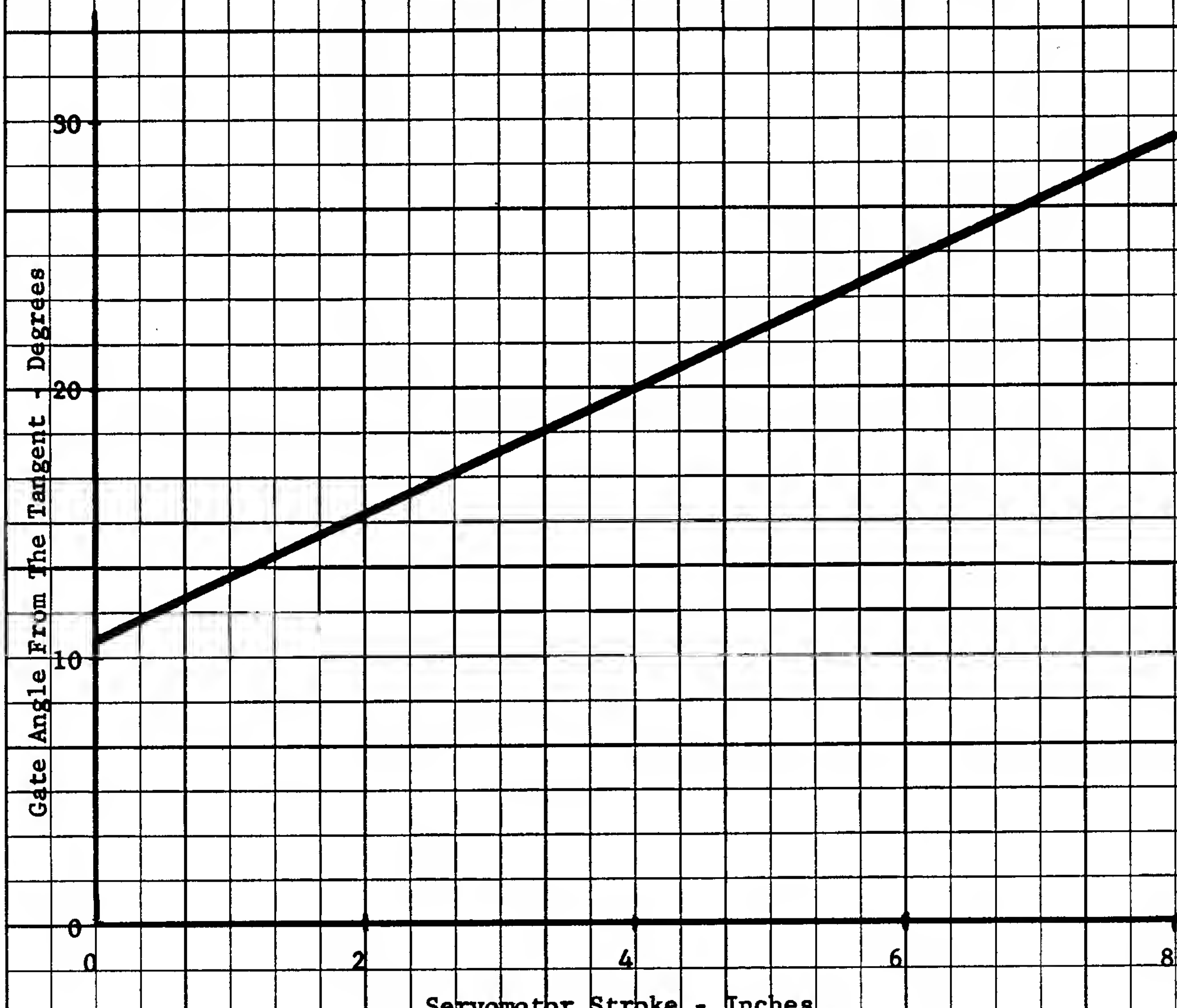


Figure 24 - Kings River Gate Positioning Mechanisms

Figure 25 - Kings River Gate Servomotor

Gate Angle vs. Servomotor Stroke



Wicket Gate Data

Effective Full Open Area	1130 sq. in.
Effective Weight	40,000 lbs.
Full Servomotor Stroke	8 in.

Figure 26

Governor

When a single hydroelectric plant supplies power to a small a.c. system requiring a constant frequency, a governor is necessary to maintain constant turbine speed under conditions of varying electrical load. If the governing mechanism maintains the same speed for all values of load, the governing is said to be isochronous. A governor so adjusted operates purely as a speed sensitive mechanism and in response to a speed change resulting from a load alteration functions to restore the desired output frequency by adjusting the wicket gate setting to suit the new load.

If two or more turbine-powered generators are operating in parallel, isochronous governing is not used because generators so arranged would not share the load properly. If the frequency of one of several such units were slightly higher, it would pick up maximum load; if the frequency were slightly lower, it would drop all load. Consider two synchronous three phase a.c. generators operating in parallel as represented in Figure 27. Only one phase need be considered since from the symmetry of the machines it is evident that whatever happens in one phase will be duplicated in the others except for a phase difference.

If the two generators are exactly in phase with equal output voltages, there will be no circulating current since E_1 and E_2 are exactly 180° out of phase. If the rotor of generator 2 is retarded, an angle α behind the other generator, the resultant loop voltage E_r will no longer be zero. A circulating current will now flow which is equal to E_r divided by the impedance of the series circuit. That is,

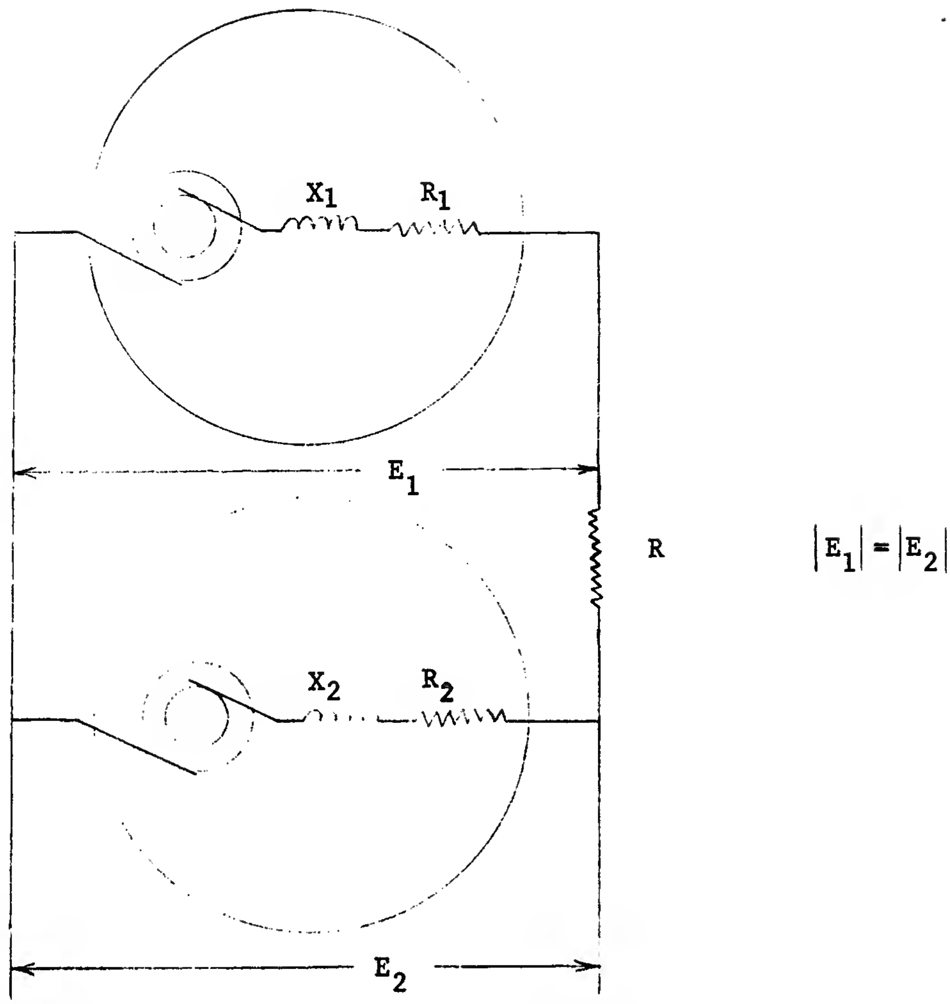
$$I = \frac{E_r}{(R_1 + R_2 + R) + j\ (X_1 + X_2)}$$

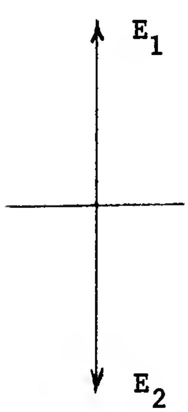
Any circulating current will lag approximately 90° behind the resultant voltage, E_r. It may be assumed that the generators now being considered have automatic voltage regulation, and hence, that they have a nearly constant output voltage. The vector diagrams in Figure 27 are then applicable and the above equation becomes

$$I = \frac{E_r - E_2}{R}$$

Although the magnitudes of the output voltages are the same, their phase difference may result in a loop voltage and current.

If E_2 is a few degrees behind E_1, a circulating current I flows which drives generator 2 as a synchronous motor and acts as a load on generator 1. Thus the circulating current creates a driving torque in the machine which is lagging and a retarding torque in the machine which is ahead.





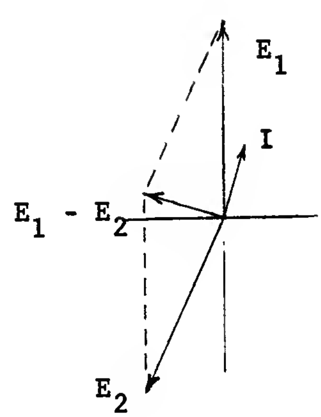


Figure 27 - Parallel Operation of AC Generators

If two astatically-governed turbine generator systems were supplying power to the same load, they would not share this load properly, since identical governing of their speeds is not possible. However, by altering the governing mechanism so that the speed of the unit is reduced a few per cent at full load as compared to the speed at no load, satisfactory operation with speed sensitive (isochronous) governors can be obtained. This fractional change in frequency, typically 1 to 5 per cent, between no load and full load is called "permanent speed droop". A turbine whose speed is controlled in this manner is said to be "output governed".

Now consider the generators in Figure 27 as being output governed. If the speed of generator 1 increases, it will move a few degrees ahead of generator 2 and pick up additional load as a result of the circulating current. However, as the wicket gates associated with this generator open to increase the flow rate, its speed will decrease. Thus, generator 1 will again be in phase with generator 2, and the circulating current will vanish. Before synchronism between the generators was re-established, generator 1 picked up only a small increment of load. If the generators had been governed astatically, generator 1 would have picked up full load since its speed would not have decreased until maximum output was reached.

With governors adjusted for output governing, it is not possible to automatically maintain a constant frequency over a range of output power. Because of speed droop, the frequency of the total electrical system must be held nearly constant by manually raising or lowering the steady state frequency for different levels of output. If the system frequency changes from 60 cycles (cycles per second) to 60.1 cycles, the wicket gates in a typical plant will be closed by the governor until the droop feedback from the gate position raises the speed setting to 60.1 cycles and wicket gate motion ceases. Also, a decrease in system frequency to 59.9 cycles would cause the gates to open until the droop action lowered the speed setting point to 59.9 cycles and stopped gate movement. From the foregoing it follows that during regulation at 100% speed at a 5% droop setting with a load requiring 50% gate opening, a 2.5% decrease in system frequency would fully open the gates and a 2.5% increase would result in closed gates. If the speed droop were set at 2.50% under the above conditions, the system frequency would have to change 1.25% above and below normal to change the turbine output from zero to full. In other words, doubling the droop setting at a particular plant reduces its load deviation by one-half for a particular change in system frequency. With speed droop governing the load change on any one plant due to a system frequency change can be varied in relation to other plants in the system by proper speed droop adjustment. Hence, fluctuations in total system demand are allocated to the constituent plants in a predetermined manner.

A Pelton hydraulic governor is used to regulate the output of the Kings River Powerhouse. This governor employs speed droop which results in regulative action as discussed above. The governor has three main controls which must be adjusted by the plant operator: (1) the steady state speed adjustment, (2) speed droop setting, (3) and the gate limit setting which is the maximum gate opening allowed by the governor for

any magnitude of system demand. Automatic emergency shutdown of the plant is achieved by reducing the gate limit setting to zero through solenoid action.

A schematic description of the governor is given in Figures 28 through 30. The governor is activated by an error in steady state frequency and subsequently returns the turbine speed to its proper value. Governor action may also be initiated by changing the manual speed setting. A spring flyball driven by a synchronous motor monitors the turbine speed to the governor. This motor is energized by a permanent magnet generator mounted on the main generator and driven through flexible couplings by the turbine shaft. Thus, the governor motor speed is proportional to the turbine shaft speed at all times. The characteristics of the spring flyball mechanism are such that the vertical displacement of the flyball collar is almost linearly related to turbine speed. The collar movement as a function of turbine speed is plotted in Figure 31.

An adjustment in speed, either manually or automatically, will cause a displacement of the pilot valve (F) relative to its cage (E). Dashpot compensation will raise and lower the pilot valve cage momentarily when the governor is moving in the opening and closing directions, respectively. Speed droop compensation is adjustable on the front of the governor cabinet and raises the pilot valve cage on increased gate openings to lower the steady state speed. The relay valve feedback linkage lowers the pilot valve cage when the relay valve (J) moves downward (in the closing direction). The cage is raised when the relay valve moves upward. The gate limit valve limits the gate servomotor opening. The servomotor is attached directly to the wicket gate ring.

Since a turbine cannot instantaneously produce required power changes for frequency adjustment, it is necessary to provide a dashpot to compensate for the lapse in time between gate relocation and return of the unit to normal speed. With too little dashpot compensation the governor will overshoot; with too much compensation the governor will be sluggish in response to speed changes. The dashpot assembly consists of two pistons in an oil filled chamber and an adjustable needle valve. A power piston (R) is connected to the restoring mechanism, and a compensating piston (M) is spring centered and attached to the pilot valve linkage. When the gates close, piston (R) moves up and creates a decreased pressure in the lower half of the dashpot housing and pulls piston (M) down. This downward movement of the compensating piston is transmitted through a link and lever to lower the pilot valve cage and temporarily raise the governor speed setting. As oil passes through the needle valve, the compensating piston returns to its centered position, and the unit reaches its normal speed. Opening of the gate servomotor reverses the procedure and temporarily lowers the governor speed setting. By opening the needle valve, the dashpot compensation is reduced and the governor may effect more rapid changes in wicket gate position. Manual speed adjustment is accomplished through the use of a control knob which raises or lowers the pilot valve cage. The relationship between pilot valve displacement and the relay valve piston velocity is indicated by Figure 32.

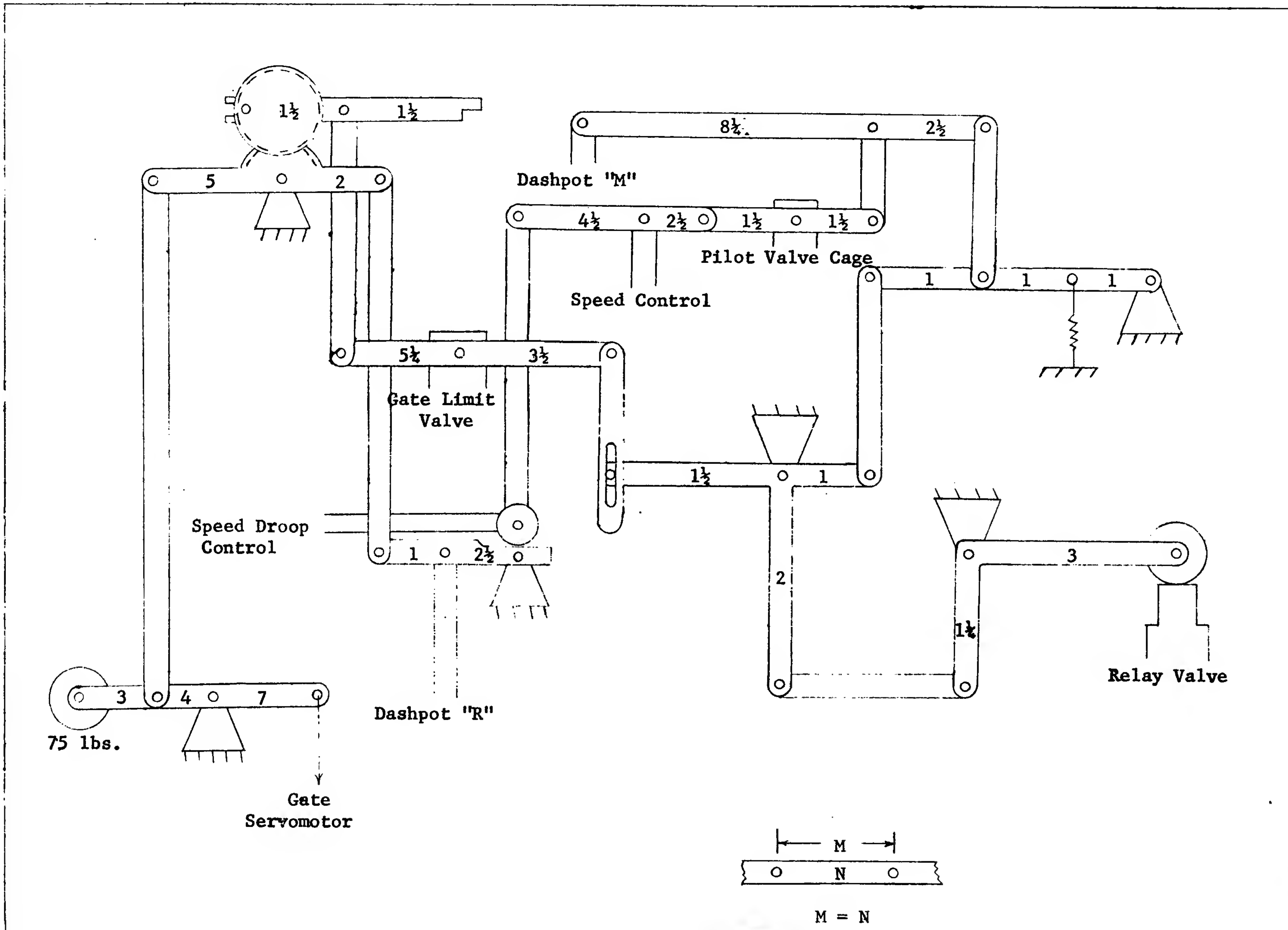


Figure 30 - Governor Linkage Schematic

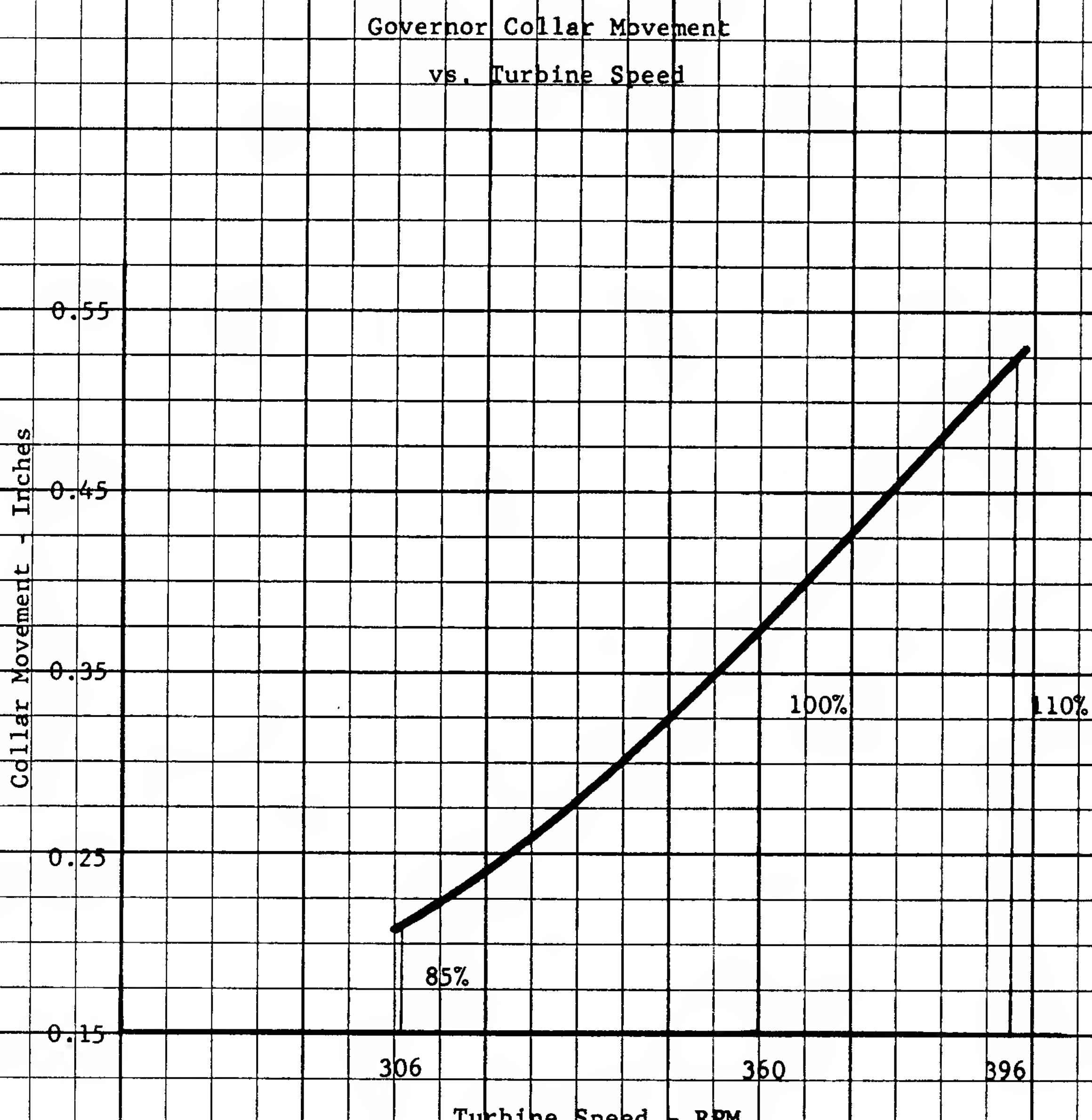

Governor Collar Movement
vs. Turbine Speed
Collar Movement - Inches
0.55
0.45
0.35
0.25
0.15
100%
110%
85%
306
360
396
Turbine Speed - RPM

Figure 31

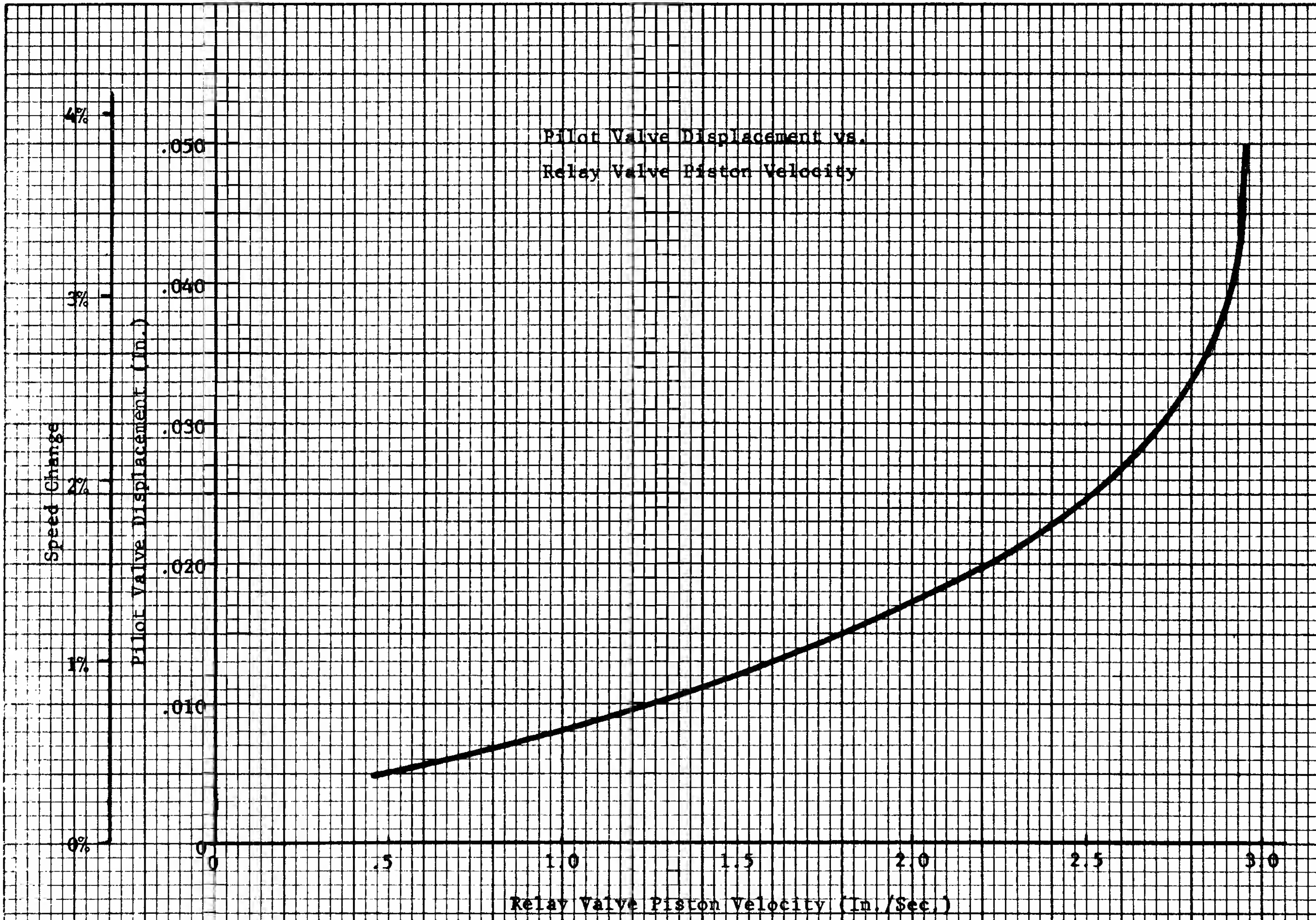

Pilot Valve Displacement vs.
Relay Valve Piston Velocity
Speed Change
4%
3%
2%
1%
0%
Pilot Valve Displacement (In.)
.050
.040
.030
.020
.010
0
.5
1.0
1.5
2.0
2.5
3.0
Relay Valve Piston Velocity (In./Sec.)

Figure 32

Speed droop is created by means of an incline and roller mechanism (N) which operates through a lever connection to change the pilot valve cage position. The slope of the incline is varied by gate servomotor movement. At zero droop the roller is positioned on the centerline of the incline pivot shaft, thus allowing the gate servomotor to travel its entire stroke without imparting vertical movement to the roller and changing the pilot valve cage position. If the speed droop is set at a non-zero value, the roller will be off the center of the incline pivot shaft, and gate motion will move the pilot valve cage with a corresponding change in turbine speed.

From the schematic diagrams it is apparent that an unobstructed flow of oil is allowed between the pilot valve and relay valve if the gate opening called for by the governor is below the gate limit setting. If the gate limit valve is lowered, it becomes effective by precluding pilot valve control. The gate limit valve controls the relay valve in a manner similar to pilot valve control. The compensating linkage between the relay valve, gate limit valve, gate limit gear (P) and gate position gear (L) is arranged to commence gate closing whenever the gate limit setting is less than gate opening. Thus, even though the flyball mechanism may call for an increase in speed, the gate limit setting will limit the actual gate opening.

Francis Reaction Turbine

Water turbines which have gained the almost exclusive consideration of hydroelectric engineers because of their suitability for driving electric generators are classified into three groups: Pelton wheels (which are impulse turbines), Propeller and Kaplan turbines, and Francis turbines. Machines in the latter two classes are reaction turbines. Any turbine can be operated under various heads, and at each head it is capable of operating at a range of speeds. For a particular head, however, there is one speed at which a given turbine will have the best efficiency, and this speed will correspond to the smoothest entry of water into the revolving runner. The range of head under which the various types of turbines will operate gives the first and primary guide to the selection of a turbine for a particular application. The total horsepower to be installed must be known and a particular turbine then chosen in view of economic considerations such as average and peak load, extent of water storage, cost of power house, convenience of operation and maintenance, and the cost of generator construction at various speeds.

The conventional Francis reaction turbine in the Kings River Powerhouse uses a runner similar to that appearing in Figure 33. The runner is mounted in a vertical shaft arrangement as illustrated by Figure 5. Various data on the unit is given below and in Figure 34. Reference 2 contains much information pertaining to the analysis and design of the Francis turbine.

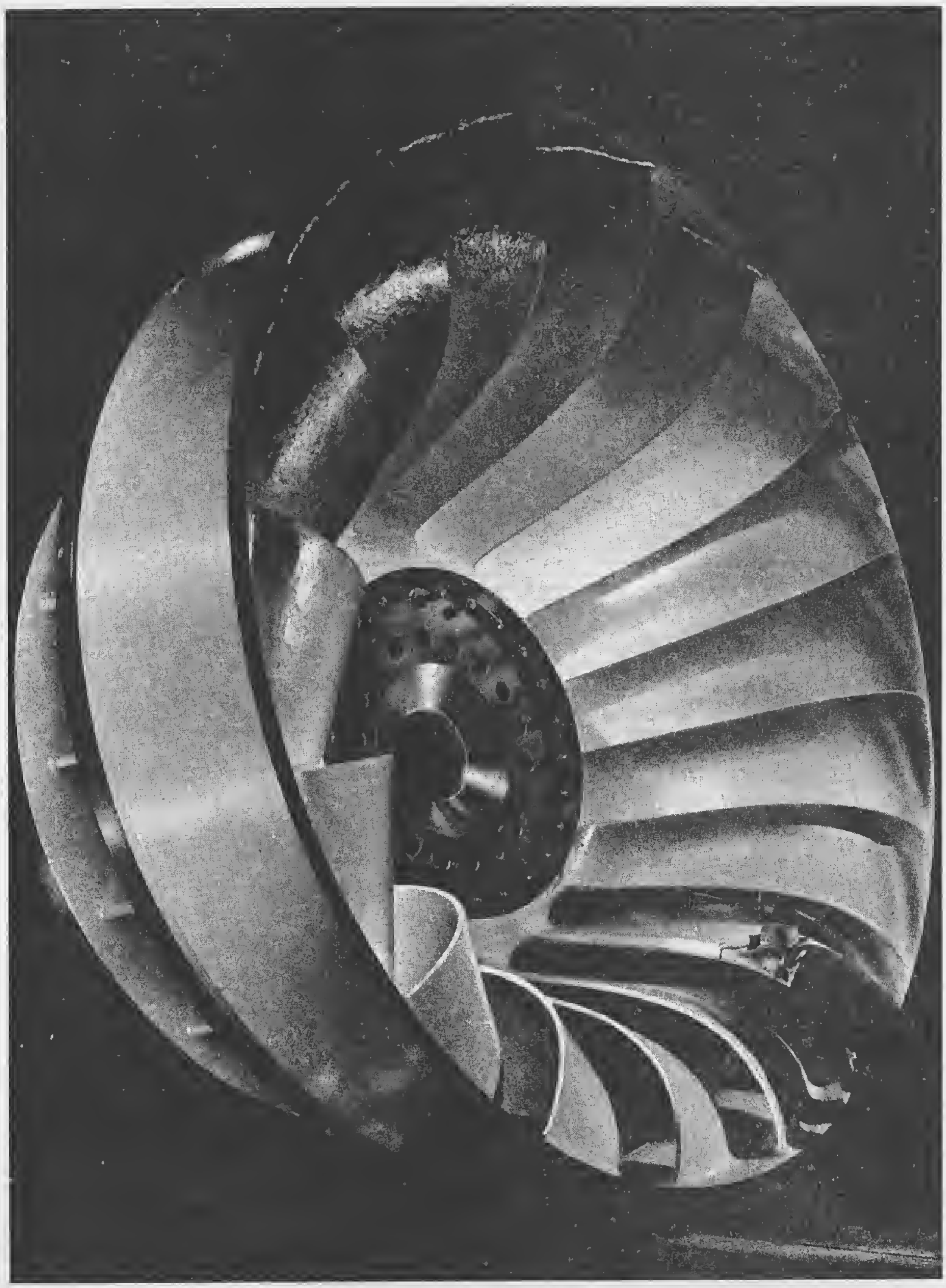


Figure 33 - A Francis Turbine Runner

Turbine Efficiency

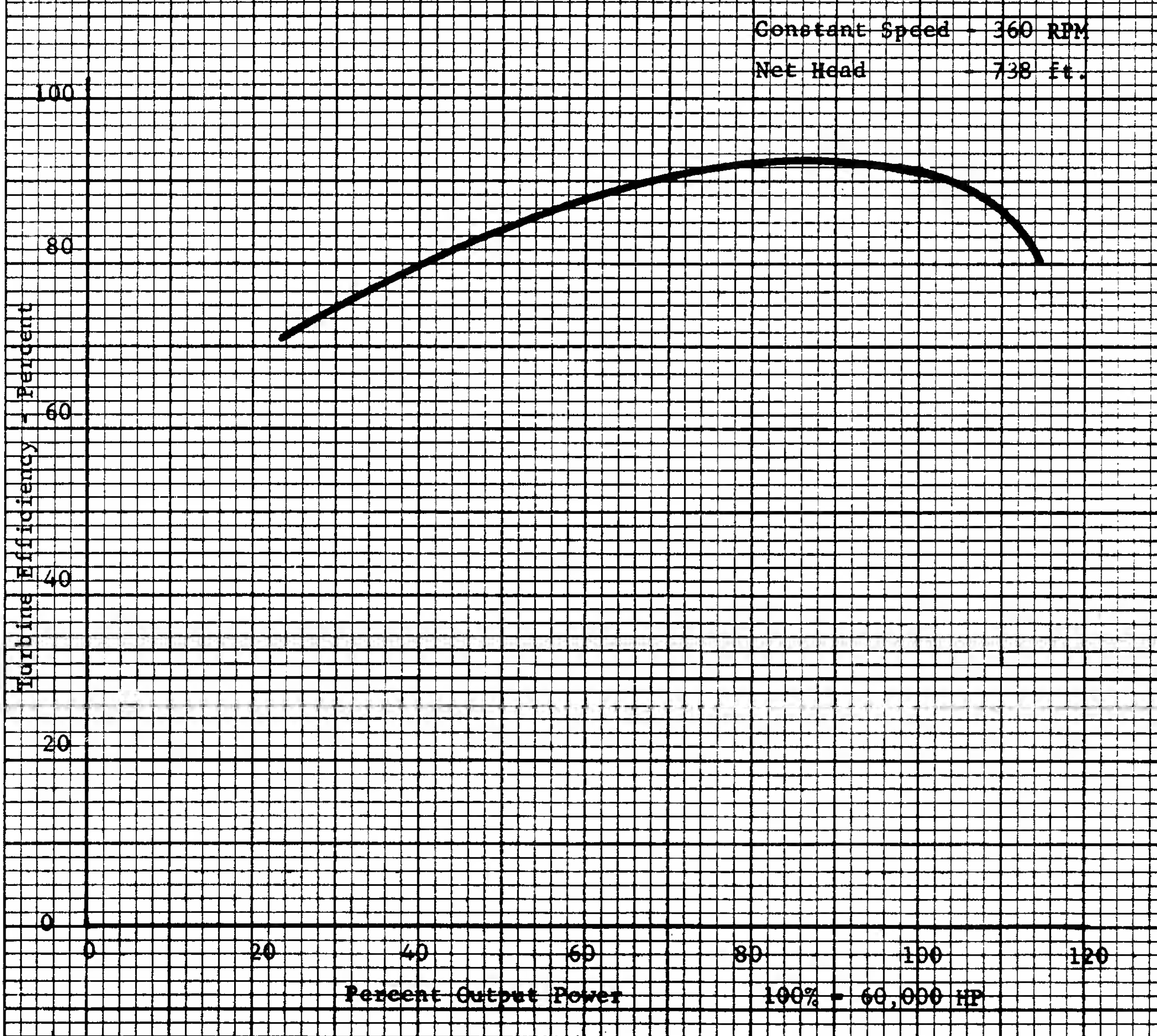


Figure 34

Turbine Characteristics

Rated speed	360 rpm
Specific speed	22.5
Rated discharge flow at net head of 738 ft. output of 60,000 hp.	780 cfs
Output power	60,000 hp
Normal tail water	3 ft. below centerline of spiral case

Generator

The generator is a three-phase synchronous type mounted vertically above the turbine as shown in Figure 5. Photographs of the rotor and stator appear in Figures 35 and 36. The generator produces 13,800 volts (line-to-line) at 60 cycles per second and has a rated power output of 49,000 KVA at .9 power factor. The rated speed is 360 rpm and the rotor has a moment of inertia of 4,230,000 lbs. ft.^{2}. The generator efficiencies are as follows:

100% rated load	97.55%
75% rated load	97.25%
50% rated load	96.45%

A self-excited DC generator provides excitation for a larger DC generator which in turn excites the large AC generator. A voltage-regulating device controls the excitation voltages and achieves an AC output voltage regulation of $\pm$ .5%.

Electrical Load Variation

A typical load variation for a system with a large proportion of industrial load is shown in Figure 37. Some noteworthy characteristics of the demand variation are the sharp rise from six to eight in the morning, the dip at noon, the sharp drop between four and five, and the rise as darkness approaches. The Kings River Project has a total output capability of 296 megawatts. To put this power in perspective, note that the city of San Francisco, California has an average electrical consumption of approximately 350 megawatts.

Figure 35 - Generator Rotor

Figure 36 - Generator Stator

ECL-16
NE 218-1

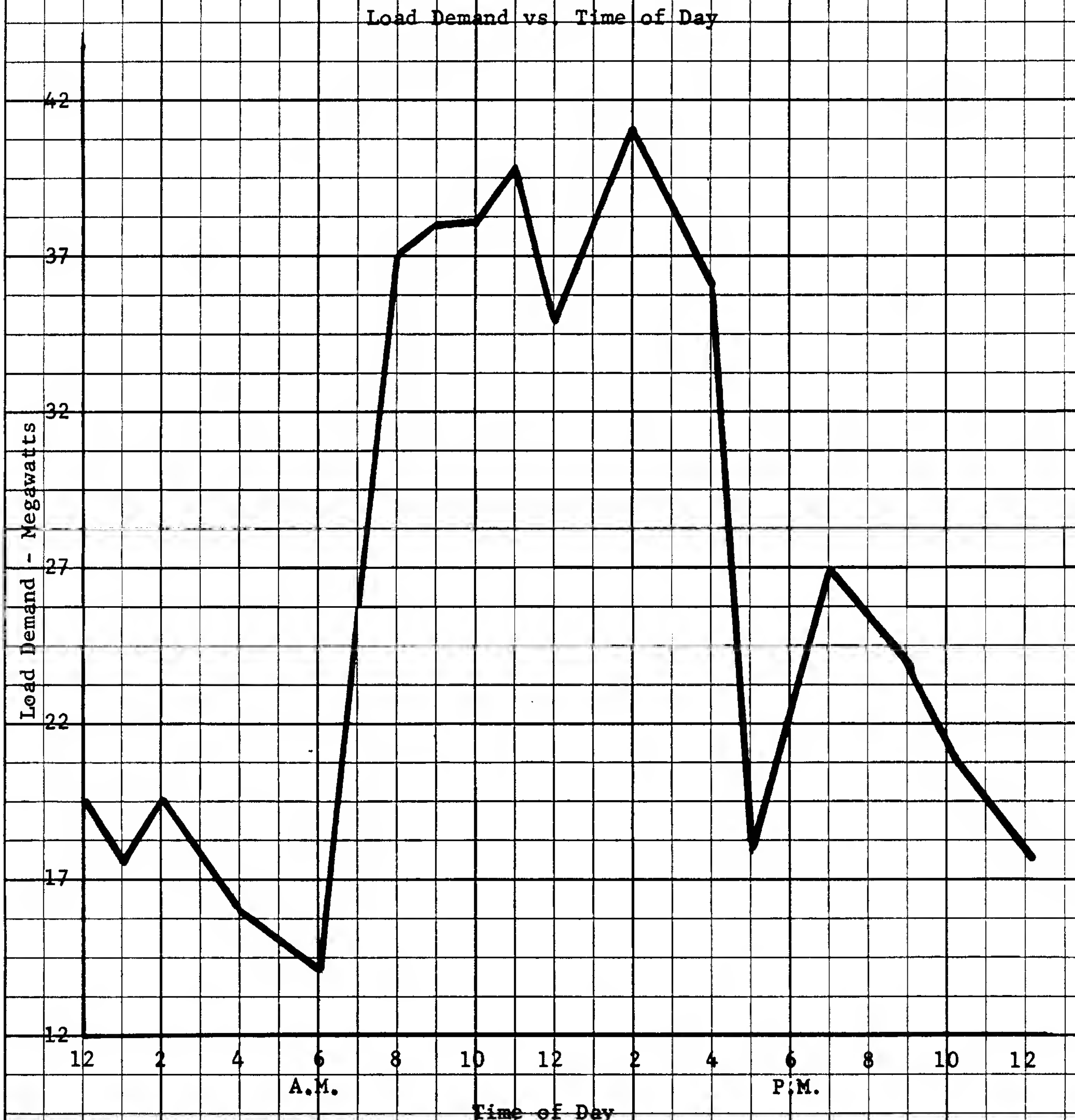


Figure 37

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